



ICAI SCHOOL OF ENGINEERING

In collaboration with the Technical University of Munich

MASTER OF SCIENCE IN INDUSTRIAL ENGINEERING

# Perspectives for Nuclear Energy in the global Energy Transition

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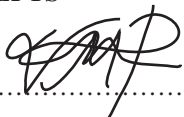
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# PERSPECTIVES FOR NUCLEAR ENERGY IN THE GLOBAL ENERGY TRANSITION

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In collaboration with: TUM – Technical University of Munich

## SUMMARY OF THE PROJECT

### PART I: A NEW NARRATIVE FOR THE ENERGY TRANSITION

Look at the big picture: **“What is the real problem that we are facing?”** **Climate change**, arguably the most vital challenge that our generation faces. Climate change is *real*, because all five key climate change indicators are changing globally, although unevenly, and faster than before. Temperatures are rising, land and sea ice are melting, sea levels are rising, all triggered by rising atmospheric CO<sub>2</sub>. This climate change is *derived from human activity*, in particular from human emissions of greenhouse gases (GHG), being CO<sub>2</sub> the most significant contributor. Human activity is the destabilising agent, which it is not all bad news: if we humans are the cause, we humans can become the solution. But do we really have reasons to care?

Is climate change such an alarming problem? Yes, it is an *alarming problem*. Global economic damages alone are shocking, but consider them together with the environmental, social and geopolitical impacts. Even though our predictions of the future are uncertain, our predictions reach overwhelmingly negative economic conclusions (global decreases of gross domestic product, unevenly distributed) and leave other alarming questions open, such as the displacement and reduction of biodiversity, human migrations or violent conflict due to resource competition. These predictions are not hopeful but are not hopeless. If we humans have triggered the problem, can we humans put the means in place to solve it?

What can we do to alleviate climate change? **We need an energy transition.** The energy sector (lifecycle emissions of fuels, mainly combustion emissions) accounts for 2/3 of all human GHG emissions, being fossil fuels the most significant contributors: coal, oil and natural gas. Accordingly, the transformation of our energy sector, known as energy transition, is at the core of climate change mitigation. On one hand, it is a transition in *energy quantity* (accessible and efficient): some countries will consume less and some will consume more, while all should enhance energy efficiency. On the other hand, it is a transition in *energy quality* (clean, reliable, affordable): shift from fossil fuels towards cleaner energy sources and electrify final energy consumption.

**The direction for the energy transition is no longer the problem. The problem now is its urgency.** Christiana Figueres acknowledged that issue: *“The question for me is not the direction, but the speed and the scale [...] We need to be at the maximum of global emissions of GHG by 2020 [...] that sounds practically impossible [...] The question is: how are we going to make it achievable?”*

Why is the energy transition so clear in theory and so messy in practice? Because the smaller war of the energy transition inside the bigger war of climate change resembles the western film **“The Good, the Bad and the Ugly”**. In the energy transition, “the good” are the popular clean and renewable energy technologies (wind and solar energy, energy storage and electric vehicles), “the bad” are the fossil fuels and “the ugly” are the forgotten technologies (such as energy demand measures and nuclear energy). The good are united but underinvested, the bad are divided but overinvested, the ugly are largely forgotten and largely underinvested.

As in the Wild West, the good alone will not defeat the bad in time. McKinsey & Company shares this vision: *“Wind, solar and geothermal energy are growing rapidly, but the world will also continue to rely on fossil fuel for decades to come”*. Unsurprisingly, big Oil & Gas companies share this vision too: *“Saudi Aramco and Royal Dutch Shell acknowledged that a shift towards renewable energy -including battery-powered cars- was under way but said oil and gas would remain indispensable for decades to come”*. It seems that now, as in the Wild West, it is time to forge alliances. Maybe the good cannot win alone but can win after all. Who could help?

Could the *bad* reach out to the good? Surprisingly yes, because the bad are divided and **Oil & Gas companies can become allies of the good**. Looking into the shorter term, Oil & Gas companies are *shifting from oil towards natural gas*, investing so heavily in liquefied natural gas (LNG) that its supply will increase by 50% between 2014 and 2021. Meanwhile, lower fossil fuel prices and shorter-term contracts have endangered the commercial viability of this LNG surge. Consequently, Oil & Gas companies have responded by *fighting coal* to make place for their gas, for example lobbying for carbon pricing. Looking into the longer term, Oil & Gas companies will become “beyond-fossil energy companies”, *diversifying into green technologies*.

The bad are divided and Oil & Gas companies can, “sooner or later”, become allies of the good. The only problem here is that this “sooner or later” has more to do with “later” than with “sooner”. Oil & Gas giants, either state-owned or publicly-owned, need time to diversify. The instability inside the OPEC countries serves as warning: if an energy transition away from fossil fuels unfolds too fast, these countries will lose their financial backbones and their geopolitical influence in the blink of an eye. The same applies at the corporate level: they are betting small on green technologies while investing big in oil and bigger in natural gas, which are still fossil fuels.

Could the *ugly* reach out to the good? Unsurprisingly yes: an ideal solution for the energy transition is **1/3 renewables, 2/3 other green technologies**. The ugly are

many (16 independent technologies, even some renewables) and diverse. Among them, the family of energy efficiency technologies, Carbon Capture and Storage (CCS) and nuclear energy should ideally lead the way.

First comes *energy efficiency* (“reduced energy intensity”), which embraces most of the ugly. Global energy intensity has been decreasing for decades, has been the main driver flattening energy-related GHG emissions since 2014 and should ideally be the main driver reducing them soon. Despite progress hitherto, 2/3 of world energy use are not regulated by efficiency standards. The coverage is geographically uneven, led by China, and sectorally uneven, fostered by the industrial and residential sectors and stalled by freight transport. The initiative of the public sector is lagging.

Second comes *CCS*, which should play an essential role if fossil fuels remain in electricity generation and industrial processes. Nonetheless, CCS is underdelivering. Its deployment will be negligible (global CCS in the 2020's may only capture the yearly CO<sub>2</sub> emissions of Cuba and New Zealand) and is mostly dedicated to enhancing fossil fuel production. CCS capacity should expand tenfold to meet the 2DS targets for 2025 and neither the private sector nor the public sector are closing the gap. The failure in Kemper County is the most visible symptom of the decreasing R&D public investment in CCS over the last few years in International Energy Agency (IEA) member countries.

Third comes *nuclear energy*, which will doubtlessly not reach the 2025 targets and will most probably not reach the 2050 targets of the International Atomic Energy Agency's (IAEA) and IEA's most ambitious scenarios. Why is this happening?

## **PART II: WHY ARE THE POSSIBLE AND THE ACTUAL STILL SO FAR APART FOR NUCLEAR ENERGY?**

On the global level, it is because two different sides of the world are pulling in two different directions. Nuclear energy is withering in the nuclear-leading half of the world (the West), whereas it is -only slowly- gathering pace in the nuclear-emerging half of the world (the East). “Nascent” reactors will be born in the East in higher number and with higher speed, “living” reactors are younger in the East and “deceased” reactors lived longer in the East. In other words, **nuclear energy as energy species is migrating from the West towards the East.**

We explain this migration by conceptualising the energy ecosystem (energy industry operations and markets as a whole) as a network of dependencies between 22 energy species and 6 stakeholders. Its species are energy species, the 22 independent technologies involved in the energy transition. Each energy species has its own genes as internal “shaping agents” (its energy development companies) that express themselves in certain internal technological features. Moreover, its environmental conditions are stakeholders, the 6 external “shaping agents” to which the energy species should better adapt. They are energy management companies, large energy users, the financial sector, policy-makers, international organisations and the civil society.

**Adaptation to the energy ecosystem and survival are connected.** Energy species whose internal technological features best match the external energy ecosystem are the energy species with the highest chances of survival. The nuclear species has 8 internal technological features that are *quite homogeneous* worldwide. 4 are potential strengths (environmental impacts, human-health impacts, grid security and geostrategy) while the other 4 are potential weaknesses (cost, waste, safety and proliferation). In parallel, the external energy ecosystem is *quite heterogeneous* worldwide.

Thus, the potential features manifest to a different extent in each region: the Eastern energy ecosystem matches better the nuclear species compared to the Western energy ecosystem. Specifically, the potential features manifest to a different extent in each country: the **national balances of manifest strengths vs. manifest weaknesses** determine the survival perspectives of nuclear energy. All national balances differ but have something in common: none is influenced by climate change mitigation. Nuclear energy has less to do with national climate morals and more to do with national needs.

**The East** hosts 3 country clusters: the Far Eastern small states (Japan, South Korea and Taiwan), the Asian emerging superpowers (China and India) and the former USSR states (Russia, Ukraine and Belarus). These 3 clusters summarise the East: they account for ~90% of its reactors and net electrical capacity in operation and for ~80% of its reactors and net electrical capacity under construction.

As for the *Far Eastern small states*, their national balances are *against* nuclear energy. Japan, South Korea and Taiwan are small, isolated states with large, foreign energy needs. They match 2 nuclear strengths (high energy density & stable fuel trade) and South Korea may match a third one (diminishing overnight construction costs), but they all mismatch 1 acute weakness (safety after the Fukushima accident and safety in relation to North Korea). Thus, Taiwan will not expand nuclear generation and will phase it out in 2025, South Korea will initially expand it and will phase it out in 2060 and Japan will gradually recover pre-Fukushima values but will delay any expansion.

As for the *Asian emerging superpowers*, their national balances are *in favour* of nuclear energy. China and India are huge countries with huge populations, emerging economies and air pollution. They match nuclear's low human-health impact (low air pollution). Additionally, China matches nuclear geostrategy (nuclear exports as part of the “One Belt, One Road” initiative) and nuclear profitability (even though cost was a potential weakness, it is a manifest strength in China, with its exemplary construction execution). Accordingly, China is building inside its borders more than 1/4 of the worldwide under-construction capacity and, beyond its borders, is exporting its domestic designs. At the same time, India is building more and larger reactors.

As for the *former USSR states*, their national balances are *in favour* of nuclear energy. They are dominated by Russia, a worldwide energy giant. Its natural gas exports towards Europe traditionally transited via Ukraine and Belarus before reaching the European market. Russia controlled the loyalty of these transit countries by controlling



their energy supply: evidently their natural gas consumption, but additionally their nuclear energy (since long in Ukraine, since recently in Belarus). The Russian energy ecosystem matches nuclear geostrategy: nuclear exports targeting mainly its international allies in fossil fuel exports (additional examples are Turkey or several OPEC countries). Although Russia has reduced its projections for domestic nuclear expansion, ROSATOM is “filling this gap” abroad and will compete with Chinese nuclear companies for the largest share of world nuclear exports.

**The West** hosts only 1 country cluster, the Western long-standing leaders (the US, Canada, the UK, France and Germany). They summarise the West: they account for ~80% of Western reactors and net electrical capacity in operation, their fleets are ageing (an average of 35 operational years) and have no replacement in sight (4 reactors under construction in them, only 6 under construction in the West). Their national balances are *against* nuclear energy: these developed, industrialised democracies may extend the life of operational reactors, but nuclear energy in the West will gradually wither.

On one side, Western nuclear energy is *solving “invisible problems” with plenty of competition to solve them*. As for environmental impacts, the Western long-standing leaders have less land footprint constraints and are rapidly deploying other low-GHG electricity sources. As for human-health impacts, their air pollution levels are very low. As for grid security, they have abundant fossil-fuel capacity at least as dispatchable and as suitable for grid frequency control. As for geostrategy, their nuclear exports will not increase as the Eastern will (although the US values nuclear technological knowledge) and they already have some of the largest “renewable hedges” against trade fluctuations (although the UK and France value the “nuclear hedge”).

On the other side, Western nuclear energy *is clashing with “visible problems” in a way unknown to any other energy species, most notably in Western Europe*. As for cost, the “Goliath-like finances” of new reactors are mismatching the preferred “David-like finances”, operational reactors are threatened by competition of renewables and gas and shut down reactors face financial uncertainty due to minimal decommissioning experience. As for safety and proliferation, the Western Europeans have lost touch with catastrophic events, hence fear them the most and hence fear nuclear accidents and nuclear weapons the most. As for waste, it is an uncertain problem worldwide that the Western confirmation bias perceives as more alarming.

We would not worry about these perspectives if climate change was under control, but it isn't, because the energy transition will not succeed in time. **We must urgently redesign the energy transition and its implementation.** Will the nuclear species have better perspectives then? We believe it could and we believe it should, because nuclear species has some of the lowest lifecycle CO<sub>2</sub>-equivalent emissions per electrical MWh. How should nuclear energy (and the energy ecosystem) evolve then? This master thesis provides the starting point to answer that question: **now we know the real problems, now we can design effective solutions.** The second part is what lies ahead for future research and we suggest some research pathways.

# PERSPECTIVAS DE LA ENERGÍA NUCLEAR EN LA TRANSICIÓN ENERGÉTICA GLOBAL

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## RESUMEN DEL PROYECTO

### PARTE I: UNA NUEVA NARRATIVA PARA LA TRANSICIÓN ENERGÉTICA

Toma perspectiva: “¿Cuál es el problema de fondo al que nos enfrentamos?”  
**Al cambio climático**, probablemente el mayor desafío de nuestro tiempo. El cambio climático es *real*, porque sus cinco indicadores clave están cambiando mundialmente - heterogéneamente- y más rápido que antes. Las temperaturas suben, los hielos terrestre y marino se derriten, los mares crecen, todo derivado de un creciente CO<sub>2</sub> atmosférico. Este cambio climático *deriva de la actividad humana*, en particular de las emisiones de gases de efecto invernadero (GHG), siendo el CO<sub>2</sub> el principal causante. La actividad humana es el agente desestabilizador, lo cual también puede leerse así: si los humanos somos causa, ¿podemos ser también solución? ¿Pero tenemos motivos para cambiar?

¿Es el cambio climático de verdad tan alarmante? Sí, es un *problema alarmante*. Las pérdidas económicas mundiales son sorprendentes en sí mismas, pero considéralas junto con los impactos ambientales, sociales y geopolíticos. Aunque predecir el futuro es incierto, nuestras predicciones esperan unánimemente pérdidas económicas (una disminución heterogénea pero global del PIB) y dejan abiertas otras cuestiones alarmantes, como el desplazamiento y la reducción de la biodiversidad, las migraciones humanas o los conflictos violentos a raíz de la competencia por los recursos. Estas predicciones desesperanzan, pero no irremediablemente. Si nosotros, los humanos, hemos causado el problema, ¿podemos también nosotros solucionarlos?

¿Cómo podemos mitigar el cambio climático? **Con una transición energética**. El sector energético (emisiones del ciclo de vida de combustibles, sobre todo durante su combustión) causa 2/3 de todas nuestras emisiones de GHG, siendo los combustibles fósiles los mayores emisores: carbón, petróleo y gas natural. En consecuencia, la transformación de nuestro sistema energético, la “transición energética”, es central en la lucha contra el cambio climático. Por un lado, es una transición en *cantidad* (accesible y eficiente): unos países consumirán menos y otros más, potenciado siempre la eficiencia energética. Por otro lado, es una transición en *calidad* (limpia, fiable y asequible): cambiar la generación fósil por generación más limpia y electrificar los consumos.



**La dirección de la transición energética ya no es el problema. El problema ahora es su urgencia.** Christiana Figueres reconocía este hecho: *“En mi opinión, el problema ya no es la dirección, sino la velocidad y el alcance [...] Necesitamos alcanzar los máximos de emisiones globales de GHG en 2020 [...] suena prácticamente imposible [...] La pregunta ahora es: ¿qué podemos hacer para conseguirlo?”*.

¿Por qué la transición energética es tan clara en teoría, tan caótica en la práctica? Porque la pequeña guerra de la transición energética dentro de la gran guerra del cambio climático se parece a la película **“El Bueno, el Feo y el Malo”**. Esta vez, “los buenos” son las tecnológicas limpias y renovables (energía eólica y solar, almacenamiento energético y vehículos eléctricos), “los malos” son los combustibles fósiles y los “feos” son las tecnologías olvidadas (como las relacionadas con la demanda energética o la energía nuclear). Los buenos están unidos pero necesitan más inversión, los malos están divididos pero les sobra inversión, los feos están olvidados y apenas tienen inversión.

Como en el Salvaje Oeste, los buenos – por sí solos- no vencerán a tiempo a los malos. McKinsey & Company comparte esta visión: *“La eólica, la solar y geotermia están creciendo rápidamente, pero el mundo seguirá dependiendo de los combustibles fósiles en las próximas décadas”*. Las grandes compañías de petróleo y gas también comparten esta visión: *“Saudi Aramco y Royal Dutch Shell admitieron que hay una transición hacia energía renovable -incluidos vehículos eléctricos-, pero que el petróleo y el gas seguirán siendo indispensables en las décadas venideras”*. Parece que ahora, como en el Salvaje Oeste, hacen falta alianzas. ¿Quién puede colaborar con los buenos?

¿Podrían cooperar los *malos* con los buenos? Sorprendentemente sí, porque los malos están divididos y las **compañías de petróleo y gas podrían aliarse con los buenos**. A corto plazo, estas compañías están *evolucionando, desde el petróleo hacia gas natural*, invirtiendo tanto en gas natural licuado (LNG) que su suministro aumentará un 50% entre 2014 y 2021. Simultáneamente, precios bajos de los fósiles y contratos a corto plazo amenazan la viabilidad comercial del LNG. Así pues, estas compañías han *arremetido contra el carbón* para hacer hueco a su gas, por ejemplo promoviendo impuestos sobre el CO<sub>2</sub>. A largo plazo, estas compañías se convertirán en “compañías energéticas más allá de los fósiles”, *diversificando hacia tecnologías limpias*.

Los malos están divididos y las compañías de petróleo y gas pueden, “antes o después”, aliarse con los buenos. El único problema es que este “antes o después” es más parecido a un “después” que a un “antes”. Estas compañías, ya públicas o privadas, necesitan tiempo para diversificar. La inestabilidad dentro de los países de la OPEC sirve como aviso: una transición rápida alejándose de los fósiles dejaría a estos países sin su columna vertebral financiera y sin su influencia geopolítica en un abrir y cerrar de ojos. Lo mismo aplica a las compañías privadas: están invirtiendo poco en tecnologías limpias, mucho en petróleo y muchísimo en gas natural, que siguen siendo fósiles.

¿Podrían cooperar los *feos* con los buenos? Naturalmente, sí: una solución ideal para la transición energética implica **1/3 renovables, 2/3 otras tecnologías limpias**. Los

feos son muchos (16 tecnologías independientes, hasta algunas renovables) y diversos. Entre ellos, las medidas de eficiencia energética, la captura y el almacenamiento de carbono (CCS) y la energía nuclear deben tomar la iniciativa.

Primera viene la *eficiencia energética* (“menor intensidad energética”), la cual incluye la mayoría de los feos. La intensidad energética global disminuye desde hace décadas, ha sido la gran responsable del estancamiento de las emisiones GHG energéticas desde 2014 y debería ser el gran responsable de reducirlas próximamente. No obstante, 2/3 del consumo energético mundial no está cubierto por estándares de eficiencia. La cobertura no es geográficamente uniforme, liderada por China, ni sectorialmente uniforme, liderado por los sectores industrial y residencial y retrasado por el transporte de mercancías. La iniciativa del sector público se está quedando atrás.

Segunda viene la *CCS*, que debe jugar un papel esencial si los fósiles perviven en la generación eléctrica y la industria. No obstante, CCS no cumple sus promesas. Su implantación es mínima (en la década de 2020, toda la CCS capturará las emisiones de CO<sub>2</sub> anuales de Cuba y Nueva Zelanda) y se dedica sobre todo a potenciar la extracción de combustibles fósiles. La capacidad de CCS debe multiplicarse por 10 para alcanzar los objetivos 2DS para 2025 y ni el sector privado ni el público están contribuyendo a ello. El fracaso en Kemper County ejemplifica la disminución en el presupuesto público de I+D en CCS en los países miembros de la Agencia Internacional de la Energía (IEA).

Tercera viene la *energía nuclear*, que no alcanzará los objetivos para 2025 -imposible- ni para 2050 -improbable-, en contra de lo que proponen la Agencia Internacional de la Energía Atómica (IAEA) y de la IEA. ¿Qué está sucediendo?

## **PARTE II: ¿POR QUÉ LO POSIBLE Y LO REAL ESTÁN TODAVÍA TAN LEJOS EN EL CASO DE LA ENERGÍA ATÓMICA?**

A nivel mundial, se debe a que dos lados del mundo están avanzando en dos direcciones diferentes. La energía nuclear está disminuyendo en su “mitad consolidada (Occidente), mientras que está aumentando -lentamente- en su “mitad emergente” (Oriente). Los reactores “nacientes” nacerán en Oriente en mayor número y velocidad, los reactores “vivos” son más jóvenes en Oriente y los reactores “difuntos” vivieron más años en Oriente. En otras palabras, **la energía nuclear como especie energética está migrando desde Occidente hacia Oriente.**

Podemos explicar esta migración imaginando el ecosistema energético (los mercados y operaciones de la industria energética) como una red de dependencias entre 22 especies energéticas y 6 stakeholders. Estas especies son especies energéticas, las 22 tecnologías independientes de la transición energética. Cada especie tiene genes como “configuradores” internos (las compañías de desarrollo energético) que se expresan en ciertas características tecnológicas internas. Más allá, sus condiciones ambientales son los stakeholders, los 6 “configuradores” externos a los que las especies energéticas deben adaptarse. Son las compañías de gestión energética, grandes consumidores energéticos, sector financiero, reguladores, agencias internacionales y la sociedad civil.

### **La adaptación al ecosistema energético y la supervivencia están conectadas.**

Las especies energéticas con características tecnológicas internas mejor adaptadas al ecosistema energético externo tienen más probabilidades de supervivencia. La especie nuclear tiene 8 características internas que son *bastante homogéneas* a nivel global: 4 potenciales fortalezas (impactos ambientales, impactos sobre la salud, estabilidad de red y geoestrategia) y 4 potenciales desventajas (coste, residuos, seguridad y proliferación). En paralelo, el ecosistema energético externo es *bastante heterogéneo* mundialmente.

Las características potenciales se manifiestan en grados distintos en cada región: el ecosistema energético oriental encaja mejor con la especie nuclear que el occidental. Específicamente, las características potenciales se manifiestan en grados distintos en cada país: los **balances nacionales de fortalezas manifiestas vs. debilidades manifiestas** determinan la supervivencia de la energía nuclear. No hay dos balances nacionales iguales, pero ninguno de ellos está influenciado por el cambio climático. La energía nuclear no tiene que ver con moral medioambiental, sí con necesidades del país.

**Oriente** alberga 3 grupos de países: los pequeños estados de Extremo Oriente (Japón, Corea del Sur y Taiwán), las superpotencias emergentes asiáticas (China e India) y la antigua URSS (Rusia, Ucrania y Bielorrusia). Estos grupos resumen Oriente: representan el ~90% de sus reactores y potencia eléctrica nuclear en operación y el 80% de sus reactores y potencia eléctrica nuclear en construcción.

Los balances nacionales de los *pequeños estados de Extremo Oriente* están *en contra* de la energía nuclear. Japón, Corea del Sur y Taiwán son estados aislados y pequeños con grandes importaciones energéticas. Encajan con la alta densidad de la energía nuclear y su comercio estable de combustible, pero desencajan con la seguridad (después de Fukushima y ante Corea del Norte). Así pues, Taiwán no expandirá su flota y cerrará sus centrales en 2025, Corea del Sur se expandirá inicialmente y cerrará sus centrales en 2060 y Japón recuperará solo gradualmente sus valores pre-Fukushima.

Los balances nacionales de las *superpotencias emergentes asiáticas* están *a favor* de la energía nuclear. China e India son países enormes con poblaciones enormes, economías emergentes y contaminación atmosférica. Encajan con el bajo impacto sobre la salud humana de la nuclear (baja contaminación atmosférica). Más allá, China encaja con la geoestrategia (exportaciones de tecnología nuclear en el marco de la “One Belt, One Road”) y la rentabilidad (a pesar de que el coste era una debilidad potencial, en China es una fortaleza, con su ejecución ejemplar de la construcción). Así pues, se están construyendo en China más de un 1/4 de la potencia nuclear en construcción y se están exportando reactores chinos. India está también construyendo más reactores.

Los balances nacionales de la *antigua URSS* están *a favor* de la energía nuclear. Están dominados por Rusia, una gigante energético mundial. Sus exportaciones de gas natural hacia Europa pasaban tradicionalmente por Ucrania y Bielorrusia antes de llegar al mercado europeo. Rusia garantizaba la lealtad de los países de tránsito controlando su suministro energético: evidentemente el de gas natural, pero también su energía nuclear

(desde hacia mucho en Ucrania, desde hace menos en Bielorrusia). Rusia encaja en consecuencia con la geoestrategia nuclear: exportaciones de tecnología nuclear hacia sus aliados internacionales en las exportaciones de combustibles fósiles (otros ejemplos son Turquía o algunos países de la OPEC). Aunque Rusia ha reducido sus proyecciones domésticas nucleares, ROSATOM está expandiéndose en el extranjero y competirá con las compañías nucleares chinas por el liderazgo del mercado internacional de reactores.

**Occidente** alberga solo un grupo de países, que llamaremos los líderes nucleares occidentales (Estados Unidos, Canadá, Reino Unido, Francia y Alemania). Estos países resumen Occidente: representan un ~80% de la generación occidental en operación, sus flotas están envejecidas (35 años de operación) y no se van a renovar pronto (4 reactores en construcción, solo 6 en construcción en todo Occidente). Sus balances nacionales están *en contra* de la energía nuclear: estas democracias desarrolladas e industrializadas quizás prolonguen la vida de sus reactores, pero su energía nuclear va a disminuir.

Por un lado, la energía nuclear occidental *resuelve “problemas invisibles” con mucha competencia para resolverlos*. En cuanto a impactos ambientales, estos países tienen menos restricciones superficiales y están escalando energías con pocas emisiones GHG. En cuanto a impactos sobre la salud humana, tienen muy baja contaminación atmosférica. En cuanto a la estabilidad de red, tienen mucha capacidad fósil al menos tan despachable y apta para el control de frecuencia. En cuanto a geoestrategia, sus exportaciones nucleares no crecerán en comparación a Oriente (aunque Estados Unidos valora la tecnología per se) y tienen varias de las mayores “coberturas renovables” frente a cambios de mercado (aunque Francia y Reino valoran la “cobertura nuclear”).

Por otro lado, la energía nuclear occidental *está chochando con “problemas visibles” como ninguna otra especie energética, especialmente en Europa occidental*. En cuanto al coste, las finanzas “estilo Goliat” de reactores nuevos pierden frente a las “estilo David”, los reactores en operación están amenazados por las renovables y el gas, los reactores cerrados tienen experiencia mínima en costes de desmantelamiento. En cuanto a seguridad y proliferación, los europeos occidentales perdieron contacto con la catástrofe, por lo que la temen especialmente, por lo que temen especialmente los accidentes y las armas nucleares. En cuanto a residuos, es un problema incierto global, pero que el sesgo de confirmación occidental percibe como más alarmante.

No nos preocuparíamos de estas perspectivas si el cambio climático estuviera controlado, pero no lo está, porque la transición energética no tendrá éxito a tiempo. **Debemos rediseñar la transición energética y su implementación.** ¿Tendrá la especie nuclear mejores perspectivas entonces? Creemos que podrá y que deberá, porque la especie nuclear tiene una de las menores emisiones de CO<sub>2</sub>-equivalente por MWh a lo largo de su ciclo de vida. ¿Cómo debería evolucionar la energía nuclear (y el ecosistema energético) entonces? Esta tesis sienta las bases para dicho análisis: **ahora conocemos el problema real, ahora podemos diseñar soluciones efectivas.** La segunda parte será fruto de investigación futura, aunque nosotros sugerimos ya algunos posibles caminos.







ICAI SCHOOL OF ENGINEERING

In collaboration with the Technical University of Munich

MASTER OF SCIENCE IN INDUSTRIAL ENGINEERING

# Perspectives for Nuclear Energy in the global Energy Transition

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Munich, January 31, 2018





***Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all***

*7.1 By 2030, ensure universal access to affordable, reliable and modern energy services*

*7.2 By 2030, increase substantially the share of renewable energy in the global energy mix*

*7.3 By 2030, double the global rate of improvement in energy efficiency*

*7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology*

*7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States and landlocked developing countries, in accordance with their respective programmes of support*

*United Nations*

*“Transforming our world: The 2030 Agenda for Sustainable Development”, [UNA15]*

*Am I confident that the world can have an economy with the prosperity levels of the rich developed world for everybody in the world on a low-carbon economy, eventually? I am absolutely, 100 percent confident.*

*Am I confident that we can get there fast enough to avoid putting so much stock of CO<sub>2</sub> into the atmosphere that we have excessive warming? I believe we can do it, but we have to try hard to meet that challenge. So, **the challenge is not if the end point is possible; it's the pace at which we've got to get there.***

*McKinsey & Company*

*“Pathways and Obstacles to a Low-Carbon Economy”, [TdPM17]*

*Transformation of the energy system in line with the “well below 2°C” objective of the Paris Agreement is technically possible but will require significant policy reforms, aggressive carbon pricing and additional technological innovation. Around 70% of the global energy supply mix in 2050 would need to be low-carbon. The largest share of the emissions reduction potential up to 2050 comes from renewables and energy efficiency, but **all low-carbon technologies (including nuclear and carbon capture and storage [CCS]) play a role.***

*International Energy Agency and International Renewable Energy Agency*

*“Perspectives for the Energy Transition”, [IEA17c]*



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# Foreword

Let me start by telling you two stories: the first one is a passage from the novel “The Hitchhiker’s Guide to the Galaxy”, the second one has less to do with Science Fiction.

Now, place yourself in this imaginary world where Artificial Intelligence seems unavoidably intelligent. There is this one computer, “Deep Thought”, the size of a small city, who is faced with this overarching question:

*“O Deep Thought computer”, he said, “the task we have designed you to perform is this. We want you to tell us...”, he paused, “The Answer.”*

*“The Answer?”, said Deep Thought. “The Answer to what?”*

*“Life!”, urged Fook.*

*“The Universe!”, said Lunkwill.*

*“Everything!”, they said in chorus.*

Deep Thought needs just a moment of reflection to realise that there is an answer, but seven and a half million years to figure the answer out. Once the wait is over, Deep Thought warns its audience that they are not going to like the answer at all.

*“All right”, said the computer, and settled into silence again. The two men fidgeted. The tension was unbearable. “You’re really not going to like it”, observed Deep Thought.*

*“Tell us!”*

*“All right”, said Deep Thought. “The Answer to the Great Question...”*

*“Yes...!”*

*“Of Life, the Universe and Everything...”, said Deep Thought.*

“Yes...!”

“Is...”, said Deep Thought and paused.

“Yes...!”

“Is...”

“Yes...!!!...?”

“Forty-two”, said Deep Thought, with infinite majesty and calm.

And a long silence follows. Both men who witnessed the answer had been training for that moment since birth, but they were not prepared for *that*.

“Forty-two!”, yelled Loonquawl. “Is that all you’ve got to show for seven and a half million years’ work?”

“I checked it very thoroughly”, said the computer, “and that quite definitely is the answer. I think the problem, to be quite honest with you, is that you’ve never actually known what the question is.”

Fair enough for now. Let’s give Deep Thought a rest after so much thinking and let’s come back to reality. I first heard of this imaginative “42” in my second year at university, several years ago. However, I had not read the whole passage until recently, when I was dealing with a less grandiose question than Life, the Universe and Everything. I was dealing specifically with one of the most controversial issues in my field of study: “Are you for or are you against nuclear energy?”. Unfortunately, I had no supercomputer to ask for advice, but I suspect that its answer would have been around 42.

I was full of opinions and lectures on Nuclear Energy, but empty of lasting conclusions. My view had shifted from *supportive* during my first year of master in Spain to *unsupportive* when I was starting my studies in Germany and to somewhat *indecisive* just one semester later. At that time, I decided to settle the question for myself (“once and for all!”, would I naively say) by writing this master thesis. Accordingly, I proposed the first draft of a topic (“*The Future of Nuclear Energy*”) to my supervisor and he agreed.

Writing this thesis has been a journey of discovery for me. I realised early on that my questions had to change, as Deep Thought would have complained. I could not just focus on being for or against nuclear energy in absolute terms and shifted my focus to the current energy transition, the one that should decarbonise our economies and alleviate climate change. Was there room for nuclear energy in this energy transition?



The more I read about the energy transition, the more it resembled that classic Wild West movies starring the good, the bad and the ugly. This movie became more exciting day by day, but also more alarming: the bad seemed so powerful and the stakes for us humans so high... The good desperately needed help, but who could help him so urgently? The ugly was there to help.

The ugly (who unsurprisingly depicts nuclear energy, as well as other “forgotten” technologies) together with the good (the most popular clean and renewable energy technologies) could, in due time, defeat the bad (the fossil fuels). Funnily enough, the bad could fleetingly help too. If you have patience, I will tell you the full Wild West movie in the following pages. You will discover that something is clearly wrong with the energy transition.

The next question came naturally: we needed help, but could we really trust the ugly? Is nuclear energy *adapted* to the new energy panorama or should it *evolve*? I said “*evolve*” because I imagined nuclear energy as a living being in an ecosystem, specifically some sort of *energy species inside an energy ecosystem*. As in evolutionary theory, an energy species has more chances of survival if its *internal technological features* match the *external energy ecosystem*. Some of the internal technological features of nuclear energy are potential strengths (environmental impacts, human-health impacts, grid security and geostrategy), some others are potential weaknesses (cost, waste, safety and proliferation) and they are matching better some regions of the energy ecosystem than others.

First, we will discuss the *symptoms*: *how* the possible and the actual are still so far apart for nuclear energy, because they are indeed so far apart.

Second, we will delve into the ultimate *causes*: *why* the possible and the actual are still so far apart for nuclear energy. We will discover that two sides of the world are pulling in opposite directions: nuclear energy is withering in the nuclear-leading half of the world (the West), whereas it is -only slowly- gathering pace in the nuclear-emerging half of the world (the East). As some species in natural ecosystems, nuclear energy as energy species is migrating from the West towards the East. The ultimate causes of this migration lie beneath: the balance of nuclear’s manifest strengths and weaknesses match better the energy ecosystem of Eastern countries and worse the energy ecosystem of Western countries. We will detail these national balances in the following pages.

Third, and very briefly, we will suggest a *treatment* in a twofold strategy: to alleviate the species-ecosystem mismatch, we can adjust the internal technological features of nuclear energy (in charge of nuclear development companies) as well as the external energy ecosystem (in charge of all the stakeholders in the energy ecosystem). We will finish these pages with a call for hope and for responsibility.

Writing this master thesis was very much like a puzzle, whose initially disconnected pieces finally came together. Nevertheless, I could not find all the pieces in the same box, not even in conventional boxes for this kind of thesis. Thus, I had to combine more than 400 references: the most credited technological sources (such as international energy organisations, Elsevier journals or OECD studies) with trustworthy sources of the energy ecosystem (such as Financial Times, the Economist or McKinsey & Company). Financial Times deserves here a special mention. Its insightful analyses serve as thread for much of the story, its vision (*“Make the right connections”*) serves as an inspiration for the whole of it. Thank you, Financial Times, for granting me permission to use your articles as references for my master thesis.

This combination of sources may surprise you, but it was the only way to see the big picture, to put *all* the pieces together. In some sense, I *just* put all the pieces together, because many others had done much of the previous work. As Sir Isaac Newton said: *“If I have seen further it is by standing on the shoulders of giants”*.

I have some words for you, dear reader. This master thesis was also written for you, as part of the energy ecosystem, at least as citizen of this common home. Let me state this very clearly: I do *not* want to hypnotise you to become an ardent supporter of nuclear energy. I want to tell you the story of the energy transition, which underlies the story of climate change. This is not a Science Fiction story. *“Climate change is no longer some far-off problem; it is happening here, it is happening now”*, in the words of Barack Obama [San15], and it is out of control despite our efforts. New energy technologies bring us hope, but will not succeed in time... In the face of this global threat, I want you to understand better nuclear energy, a possible *partial* solution that is justifiably falling short of expectations.

Lastly, a few gratitude words. I never have enough gratitude words for *my family*, for the endless love of my parents (Matilde and Jesús) and my grandparents (Matilde & Ramiro, Agustina & Simón). Their sacrifices are the foundation of any success I may meet, they are honorary authors of this master thesis (this is particularly curious: my grandparents never had the opportunity to study beyond school, but now they have co-authored a master thesis for one of the most prestigious technical universities in Germany).

I have gratitude words for *my teachers*: my supervisor in Germany, Rafael Macián, and my coordinator in Spain, José Ignacio Linares, for their trust, patience and feedback. I have gratitude words for *my friends* too. Most remarkably for Pablo Bullido, because sharing so many study hours and talking-about-whatever pauses made these months much more entertaining. Also for Javier Sánchez-Collado, for our enriching discussions about climate change topics and ethical implications. And so many more that I will not individually mention: thank you all. Last but not least, thank you, Google, my “staircase to the shoulders of giants”.

# Executive Summary

Look at the big picture: “**What is the real problem that we are facing?**” **Climate change**, arguably the most vital challenge that our generation faces. Climate change is *real*, because all five key climate change indicators are changing globally, although unevenly, and faster than before. Temperatures are rising, land and sea ice are melting, sea levels are rising, all triggered by rising atmospheric CO<sub>2</sub>. This climate change is *derived from human activity*, in particular from human emissions of greenhouse gases (GHG), being CO<sub>2</sub> the most significant contributor. Human activity is the destabilising agent, which it is not all bad news: if we humans are the cause, we humans can become the solution. But do we really have reasons to care?

Is climate change such an alarming problem? Yes, it is an *alarming problem*. Global economic damages alone are shocking, but consider them together with the environmental, social and geopolitical impacts. Despite the fact that our predictions of the future are uncertain, our predictions reach overwhelmingly negative economic conclusions (global decreases of gross domestic product, unevenly distributed) and leave other alarming questions open, such as the displacement and reduction of biodiversity, human migrations or violent conflict due to resource competition. These predictions are not hopeful, but are not hopeless. If we humans have triggered the problem, can we humans put the means in place to solve it?

What can we do to alleviate climate change? **We need an energy transition**. The energy sector (lifecycle emissions of fuels, mainly combustion emissions) accounts for 2/3 of all human GHG emissions, being fossil fuels the most significant contributors: coal, oil and natural gas. Accordingly, the transformation of our energy sector, known as energy transition, is at the core of climate change mitigation. On one hand, it is a transition in *energy quantity* (accessible and efficient): some countries will consume less and some will consume more, while all should enhance energy efficiency. On the other hand, it is a transition in *energy quality* (clean, reliable, affordable): shift from fossil fuels towards cleaner energy sources and electrify final energy consumption.

We all seem to know what to do. **The *direction* for the energy transition is no longer the problem. The problem now is its *urgency*.** Christiana

Figueres acknowledged that issue: *“The question for me is not the direction, but the speed and the scale [...] We need to be at the maximum of global emissions of GHG by 2020 [...] that sounds practically impossible [...] The question is: how are we going to make it achievable?”*.

Why is the energy transition so clear in theory and so messy in practice? Because the smaller war of the energy transition inside the bigger war of climate change resembles the western film **“The Good, the Bad and the Ugly”**. In the energy transition, “the good” are the popular clean energy technologies (wind and solar energy, energy storage and electric vehicles), “the bad” are the fossil fuels and “the ugly” are the forgotten technologies (such as energy demand measures and nuclear energy). The good are united but underinvested, the bad are divided but overinvested, the ugly are largely forgotten and largely underinvested.

As in the Wild West, the good *alone* will not defeat the bad *in time*. McKinsey & Company shares this vision: *“Wind, solar and geothermal energy are growing rapidly, but the world will also continue to rely on fossil fuel for decades to come”*. Unsurprisingly, big Oil & Gas companies share this vision too: *“Saudi Aramco and Royal Dutch Shell acknowledged that a shift towards renewable energy — including battery-powered cars — was under way but said oil and gas would remain indispensable for decades to come”*. It seems that now, as in the Wild West, it is time to forge alliances. Maybe the good cannot win alone, but can win after all. Who could collaborate with the good?

Could the *bad* reach out to the good? Surprisingly yes, because the bad are internally divided and **Oil & Gas companies could become unexpected allies of the good**. Looking into the shorter term, Oil & Gas companies are *shifting from oil towards natural gas*, investing so heavily in liquefied natural gas (LNG) that its supply is on course to increase by 50% between 2014 and 2021. Meanwhile, lower fossil fuel prices and shorter-term contracts have endangered the commercial viability of this LNG surge. As a consequence, Oil & Gas companies have immediately responded by *fighting coal* to make place for their gas, for example lobbying for carbon pricing mechanisms. Looking into the longer term, Oil & Gas companies will become “beyond-fossil energy companies”, *diversifying into green technologies*.

The bad are internally divided and Oil & Gas companies could, “sooner or later”, become unexpected allies of the good. The only problem here is that the “sooner or later” just mentioned has more to do with “later” than with “sooner”. Oil & Gas giants, either state-owned or publicly-owned, need time to diversify. The instability inside the OPEC countries serves as warning: if an energy transition away from fossil fuels unfolds too fast, these countries will lose their financial backbones and their geopolitical influence in the blink of an eye. The same applies at the corporate level: they are betting small on green technologies while investing big in oil and bigger in natural gas, which are still fossil fuels.

The bad need time to diversify and the energy transition cannot afford to give away more time: we know the direction, the problem now is the urgency. The good will surely appreciate this help of the bad, but that will not be enough.

Could the *ugly* reach out to the good? Unsurprisingly yes: an ideal solution for the energy transition is **1/3 renewables, 2/3 other green technologies**. The ugly are many (16 independent technologies, even some renewables) and diverse. Among them, the family of energy efficiency technologies, Carbon Capture and Storage (CCS) and nuclear energy should ideally lead the way.

First comes *energy efficiency* (“reduced energy intensity”), which embraces most of the ugly. Global energy intensity has been decreasing for decades, has been the main driver flattening energy-related GHG emissions since 2014 and should ideally be the main driver reducing them in the near future. Despite progress hitherto, 2/3 of world energy use are not regulated by efficiency standards. The coverage is geographically uneven, led by China, and sectorally uneven, fostered by the industrial and residential sectors and stalled by freight transport. The public and the private sector are united, but the public sector initiative is lagging behind.

Second comes *CCS*, which should play an essential role if fossil fuels remain in electricity generation and industrial processes. Nonetheless, CCS is coming short of expectations. Its deployment will likely be negligible (global CCS in the 2020’s may only capture the yearly CO<sub>2</sub> emissions of Cuba and New Zealand) and, funnily enough, CCS is mostly dedicated to enhancing fossil fuel production. CCS capacity should expand tenfold to meet the 2DS targets for 2025 and neither the private sector nor the public sector are closing the gap. The failure in Kemper County is the most visible symptom of the decreasing R&D public investment in CCS over the last few years in International Energy Agency (IEA) member countries.

Third comes *nuclear energy*, which will doubtlessly not reach the 2025 targets and will most probably not reach the 2050 targets of the International Atomic Energy Agency’s (IAEA) and IEA’s most ambitious scenarios. Why are the possible and the actual still so far apart?

On the *global level*, it is because two different sides of the world are pulling in two different directions. Nuclear energy is withering in the nuclear-leading half of the world (the West), whereas it is -only slowly- gathering pace in the nuclear-emerging half of the world (the East). “Nascent” reactors will be born in the East in higher number and with higher speed, “living” reactors are younger in the East and “deceased” reactors lived longer in the East. In other words, **nuclear energy as energy species is migrating from the West towards the East**.

We will explain this migration by conceptualising the energy ecosystem (energy industry operations and markets as a whole) as a network of dependencies between

its 22 energy species and its 6 stakeholders. Its species are energy species, the 22 independent technologies involved in the energy transition. Each energy species has its own genes as internal “shaping agents” (its energy development companies) that express themselves in certain internal technological features. Moreover, its environmental conditions are stakeholders, the 6 external “shaping agents” to which the energy species should better adapt. They are energy management companies, large energy users, the financial sector, policy-makers, international organisations and the civil society.

As the energy ecosystem changes (due to endogenous changes in the energy species or exogenous changes in the stakeholders), the energy transition unfolds. In this ecosystem-wide evolution, **adaptation to the energy ecosystem and survival are connected**. Energy species whose internal technological features best match the external energy ecosystem are the energy species with the highest chances of survival.

In short, nuclear energy has 8 internal technological features that are fairly *homogeneous* worldwide (as any species whose genes hardly vary in space and time). 4 of the features are potential strengths (environmental impacts, human-health impacts, grid security and geostrategy) while the other 4 are potential weaknesses (cost, waste, safety and proliferation). In parallel, the external energy ecosystem is fairly *heterogeneous* worldwide (as any ecosystem whose environmental conditions vary in space and time). Thus, the potential features manifest to a different extent in each region, in each country. These **national balances between manifest strengths and manifest weaknesses** determine the survival perspectives of nuclear energy.

This conceptual framework explains nuclear migration. On the *regional level*, the Eastern energy ecosystem matches better nuclear energy as energy species than the Western energy ecosystem, even though Eastern national balances differ greatly one from another. All national balances may differ, but they have something in common: none of them is influenced by climate change mitigation. Nuclear energy has less to do with national climate morals and more to do with national needs. On the *national level*, we identify 4 geographical country clusters that explain why the regional balances are in favour in the East and against in the West.

**The East** hosts 3 clusters: the Far Eastern small states (Japan, South Korea and Taiwan), the Asian emerging superpowers (China and India) and the former USSR states (Russia, Ukraine and Belarus). These 3 clusters summarise the East: they account for  $\approx 90\%$  of its reactors and net electrical capacity in operation and for  $\approx 80\%$  of its reactors and net electrical capacity under construction.

As for the *Far Eastern small states*, their national balances are *against* nuclear energy. Japan, South Korea and Taiwan are small, isolated states with large, foreign energy needs. They match 2 nuclear strengths (high energy den-

sity & stable fuel trade) and South Korea may match a third one (diminishing overnight construction costs), but they all mismatch 1 acute weakness (safety after the Fukushima accident and safety in relation to North Korea). Accordingly, Taiwan will not further expand nuclear generation and will phase it out in 2025, South Korea will initially expand it and will phase it out in 2060 and Japan will gradually recover pre-Fukushima values but will delay a potential expansion.

As for the *Asian emerging superpowers*, their national balances are *in favour* of nuclear energy. China and India are huge countries with huge populations and emerging economies, where air pollution emerged too. Thus, China and India match nuclear's low human-health impact (low air pollution). Additionally, China matches 2 further nuclear strengths: its geostrategy (international nuclear exports as part of the "One Belt, One Road" initiative) and its profitability (even though cost was a potential weakness, it is a manifest strength in China, with its exemplary normalised construction times for domestic and international contractors).

Accordingly, both countries will likely drive worldwide nuclear expansion in the next years: India is building more and larger reactors, while China is building inside its borders more than 1/4 of the worldwide under-construction capacity and, beyond its borders, is exporting its domestic designs.

As for the *former USSR states*, their national balances are *in favour* of nuclear energy. The former USSR states are dominated by Russia, a worldwide energy giant, with extensive fossil fuel resources that are extensively exploited and traded. Its natural gas exports towards Europe traditionally transited via Ukraine and Belarus before reaching the European market, the stronghold of Russian energy exports. Russia controlled the loyalty of these transit countries by controlling their energy supply: evidently their natural gas consumption, but additionally their nuclear energy (since long in Ukraine, since recently in Belarus).

This is why Russian energy ecosystem matches 1 nuclear strength, geostrategy (boosting technology knowledge and exports). As Chinese nuclear policy is targeting mainly "One Belt, One Road" countries, the Russian one is targeting mainly its international allies in fossil fuel exports (additional examples are Turkey or several OPEC countries). Accordingly, although Russia has reduced its projections for domestic nuclear expansion, ROSATOM is "filling this gap" abroad and will compete with Chinese nuclear companies for the largest share of world nuclear exports.

**The West** hosts only 1 cluster: the Western long-standing leaders (the US, Canada, the UK, France and Germany). This single cluster summarises the West: it accounts for  $\approx 80\%$  of Western reactors and net electrical capacity in operation, its fleet is ageing (35 operational years on average) and has no generational replacement in sight (only 4 reactors under construction in these 5 countries, only 6 reactors under construction in the whole West).

As for the *Western long-standing leaders*, their national balances are *against* nuclear energy. The US, Canada, the UK, France and Germany are developed, industrialised democracies, where nuclear energy has invisible strengths and visible weaknesses. They may extend the life of operational reactors, but nuclear energy in the West will gradually wither.

On one side, Western nuclear energy is solving “invisible problems” with plenty of competition to solve them. As for environmental impacts, the Western long-standing leaders have less land footprint constraints (compared to the Far Eastern small states) and are rapidly deploying other low-GHG electricity sources. As for human-health impacts, their air pollution levels are very low (compared to Eastern and Southern Asia). As for grid security, they have abundant fossil-fuel capacity at least as dispatchable and as suitable for grid frequency control as nuclear energy. As for geostrategy, they will not increase nuclear exports as much as the Eastern counterparts (although the US values nuclear technological knowledge) and they already have some of the largest “renewable hedges” against trade fluctuations (although the UK and France value the “nuclear hedge”).

On the other side, Western nuclear energy is clashing with “visible problems” in a way unknown to any other energy species, most notably in Western Europe. As for cost, the “Goliath-like finances” of new reactors are mismatching the preferred “David-like finances”, operational reactors are threatened by growing competition of renewables and gas (mainly in the US, presumably in Germany and the UK) and shut down reactors are mired with financial uncertainty due to minimal decommissioning experience. As for safety and proliferation, the Western Europeans have lost touch with catastrophic events, hence fear them the most and hence fear nuclear accidents and nuclear weapons the most. As for waste, it is an uncertain problem worldwide that the Western confirmation bias perceives as more alarming.

In a nutshell, **nuclear energy will survive on the global stage, but is in the middle of its great migration**. Nuclear energy as energy species is migrating from the West towards the East: “nascent” reactors will be born in the East in higher number and with higher speed, “living” reactors are younger in the East and “deceased” reactors lived longer in the East. Nuclear energy will survive, but will fall short of IAEA’s and IEA’s most ambitious scenarios.

In the near future, nuclear energy will thrive in the Asian emerging superpowers (China and India) and, to a lesser extent, in the former USSR states (Russia, Ukraine and Belarus), whereas nuclear energy will gradually -and not immediately- wither in the Western long-standing leaders and the Far Eastern small states. Nuclear energy may well find new migratory destinations, mainly in the East, led by Chinese nuclear policy (targeting mainly “One Belt, One Road” countries) and Russian nuclear policy (targeting, among others, its international allies in fossil fuel exports).



We would not worry about these perspectives if climate change was under control. However, climate change is indeed out of control: the good will not defeat the bad *in time*, while some of the bad -namely, Oil & Gas companies- may help but *need time* to diversify and all of the ugly are *underperforming*. We must **urgently redesign the energy transition and its implementation**.

Will the nuclear species have better perspectives in a redesigned, ever-changing energy transition? We believe it could and we believe it should, because nuclear species has some of the lowest lifecycle CO<sub>2</sub>-equivalent emissions per electrical MWh. How should nuclear energy (and the energy ecosystem) evolve then? This master thesis provides the starting point to answer that question: **now we know the real problems, now we can design effective solutions. The second part is what lies ahead for future research**. Lastly, we leave the survival perspectives behind (migration from the West towards the East) and briefly imagine how the evolutionary perspectives may look like (growth in the East, healing in the West).



# Part I

## A new narrative for the energy transition



# Chapter 1

## Back to Basics: from climate change to energy transition

We have already introduced the energy transition, the one that should decarbonise our economies and alleviate climate change. We will now take a step towards where it “all began”: climate change. Climate change is arguably *the most vital challenge* that our generation faces. Its transcendence must lead us into immediate action, putting into perspective the secondary effects of the solutions. Nuclear energy will arise as an underestimated solution to this severe problem that we are not solving properly. Take perspective: “What is the real problem that we are facing?”

Hence we have to agree on climate change or else this thesis will be a non-sense. We will explain the extent of climate change (*is it real?*), its consequences (*is it an alarming problem?*) and the possible solutions (*what can we do to alleviate it?*). Among the best solutions is this current energy transition, that we will describe in high level in this chapter and develop “as a Wild West movie” in the next chapter.

### 1.1 Is climate change real?

Measuring climate change seems certainly complex. There are many related *phenomena*, such as changing atmospheric weather patterns, changing biodiversity or rising sea levels. Each of these phenomena has many *measurement possibilities*: for atmospheric weather patterns we could measure for example the incidence of extreme weather events, yearly precipitation or average temperatures. Besides, each of these phenomena has many *influencing factors*, that might be seasonal and not necessarily derived from human activity. Where can we possibly start?

Fortunately, there are five indicators that encapsulate all the rest: the “key climate change indicators” or “vital signs of the planet”. We will divide them into 3 groups: 1) global surface temperatures, 2) global indexes of ice and sea (Arctic sea ice minimum, land ice and sea levels) and 3) carbon dioxide (CO<sub>2</sub>) in the atmosphere.

We can accurately measure these five key climate change indicators. Weather stations, ships, buoys and satellites measure temperatures worldwide [Dav17]. Different types of satellites measure the different global indexes of ice and sea: the Arctic sea ice minimum [SNb], land ice [NASg] and sea levels (which are also available from coastal tide gauges) [fSSa]. Lastly, we can measure atmospheric CO<sub>2</sub> from Earth [ON] and Space [atCIoT].

Our measurements show that these five indicators are changing beyond usual fluctuations. They are breaking records, a recent evidence of a longer-term trend: climate has been changing for decades and, lately, is *changing faster than before*.

On one hand, 16 of the 17 warmest years in the 136-year record all have occurred since 2001. In fact, the year 2016 was the warmest on record [fSSb]. See the trend for yourself looking at Figure 1.1. Four international research institutions (NASA and NOAA in the US, Hadley Center in the UK and the Japanese Meteorological Agency in Japan) agree on this trend [NASH]. Earth is warming, not evenly warming, but indeed globally warming.

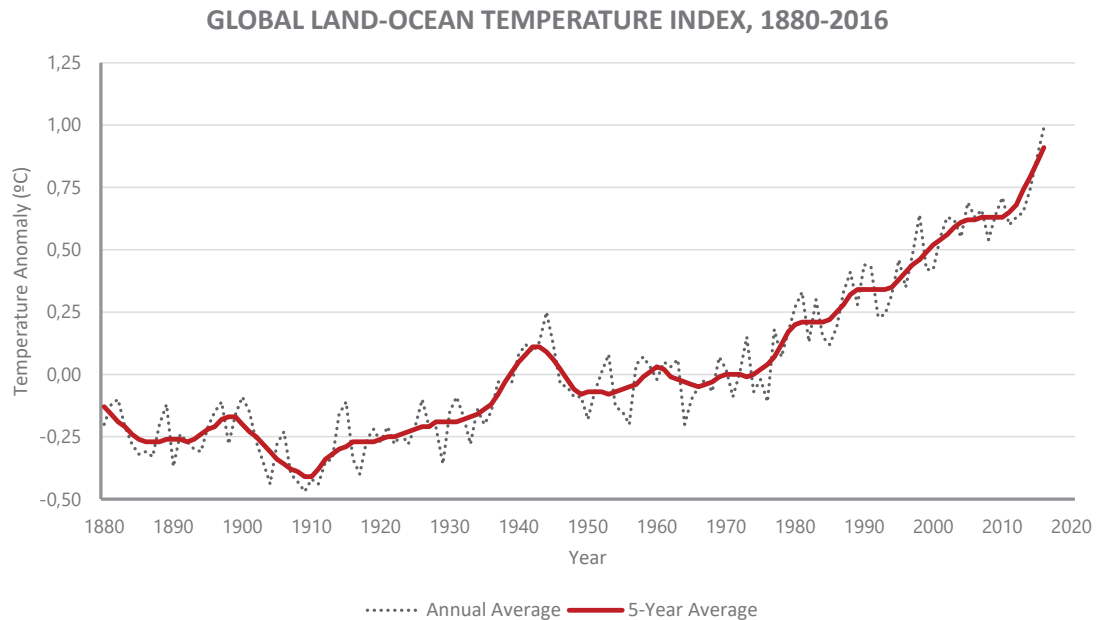


Figure 1.1: Change in global surface temperature, relative to the 1951-1980 annual average of temperatures. Data from NASA/GISS [fSSb]

On the other hand, as Earth is warming *in aggregate scale*, ice is melting and seas are rising also *in aggregate scale*. This consequence seems intuitively true, but we will show that it is also scientifically true. As the US statistician W. Edwards Deming proclaimed: *“In God we trust, all others (must) bring data”*. Fair enough, let’s bring you the data.

We will begin with the Arctic sea ice extent. This extent undergoes short-term seasonal variations (increases during winter, shrinks during summer) inside a long-term diminishing trend: the annual minimum ice coverage (typically in September) has been declining at a rate of 13.3 percent per decade in the 38-year record [SNb]. See the trend for yourself looking at Figure 1.2, where we compare the annual minimum of 1984 with that of 2012.

Moreover, the extent is just one side of the coin. The other side of the coin is the thickness. Arctic sea ice it is not only shrinking in surface, but it is also becoming thinner, which is a synonym of becoming *younger* when dealing with ice. *“We’ve lost most of the older ice: in the 1980’s, multiyear ice made up 20 percent of the sea ice cover. Now [in 2016] it’s only about 3 percent”*, in the words of one of the cryospheric scientist at NASA Goddard Space Flight Center [Viñ16]. The remaining multiyear Arctic ice is increasingly dispersed, woven into younger ice, and thus it is much easier to melt than it was years ago [Viñ16].

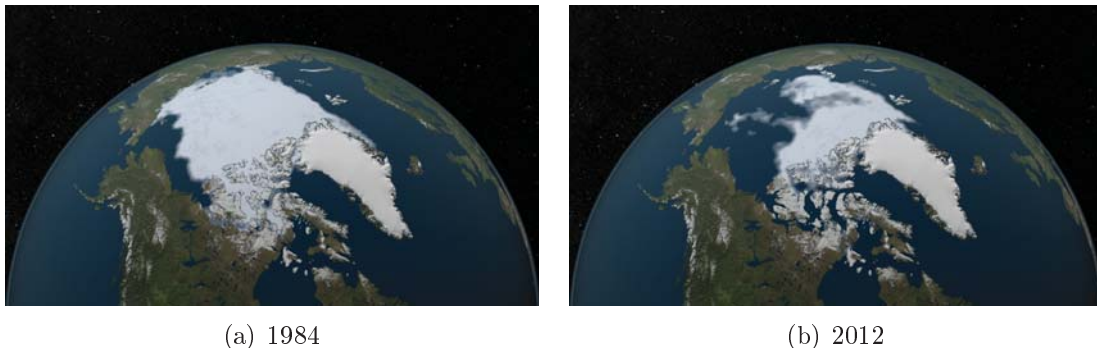


Figure 1.2: The minimum Arctic sea ice coverage for 2012 set a record low since at least 1979, when satellites started their records. *“At the rate we’re observing this decline”*, said NASA scientist Joey Comiso, *“it’s very likely that the Arctic summer sea ice will completely disappear within this century”* [NASa]

Sea ice, mainly in the Arctic, is not the only ice melting. Land ice, mainly in Antarctica and Greenland but also in worldwide glaciers, is also melting. Land ice behaves differently than sea ice for geographical and climatological reasons, but follows anyway the same long-term diminishing trend. Land ice mass in Antarctica and Greenland has been steadily shrinking in the 14-year record, an average of a couple of hundreds Gigatons per year [NASg], which is a measure that human everyday experience cannot visualise.

Let's try to exemplify these colossal measures using a “colossal” reference: the Burj Khalifa, the tallest building on Earth (828 meters). If you ever wondered that, the Burj Khalifa has an empty weight of approximately 500000 tons (or 0.0005 Gigatons) [BUR]. With that reference in mind, Antarctica loses each year an average of 250000 Burj Khalifas (127 Gigatons), *each year* since 2002. Greenland loses even more ice mass: each year an average of 570000 Burj Khalifas (287 Gigatons), *each year* since 2002. See the trend for yourself looking at Figure 1.3: land ice is diminishing and, lately, is *diminishing faster than before*.

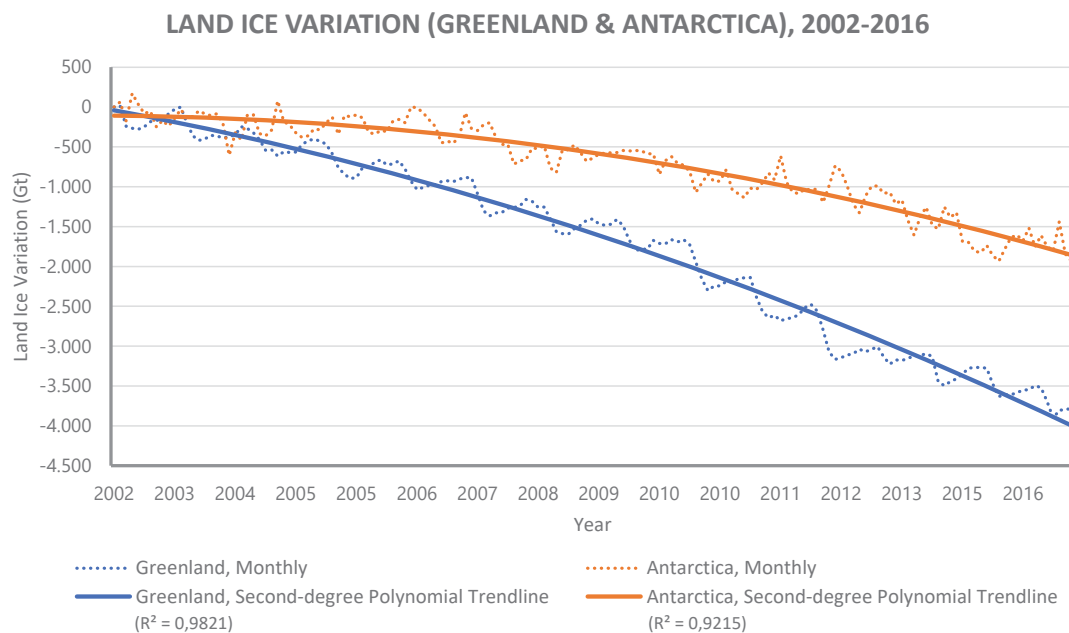


Figure 1.3: Change in land ice mass in Greenland and Antarctica between 2002 and 2016. Data from NASA (GRACE satellite data) [NASg]

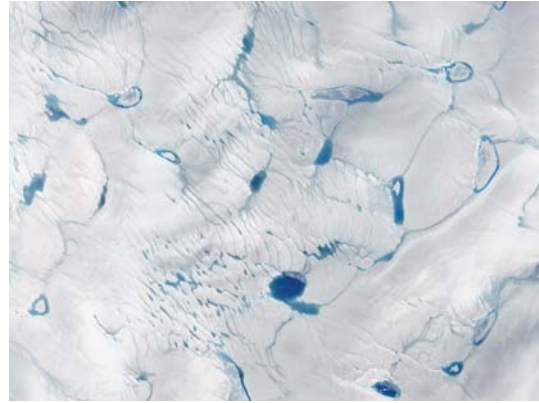
Ice melting affects worldwide climate. Earth *absorbs more heat* from the Sun (less sunlight reflection due to colour change of Earth's surface), *redistributes heat less efficiently* across Earth's regions (worse oceanic and atmospheric circulation) and has *higher sea levels* (because of higher temperatures and land ice melting).

**Alteration of Sun-Earth heat exchange** As ice sheets melt down, ice *white* colour is substituted by *darker* colours: light gray from incipient melting ice (Figure 1.4), cobalt blue from water streams over ice (Figure 1.4) or dark navy blue as standard ocean colour (Figure 1.5). These darkened surfaces have lower albedo values: less reflection and more absorption of sunlight. Temperatures thus rise and more ice melts, a self-reinforcing mechanism. Worryingly, white ice surface is diminishing in aggregate scale (although unevenly in geographical terms) [Viñ17].





(a) June 10, 2014



(b) June 15, 2016

Figure 1.4: In the middle of Greenland. Same place & month, different years [NASf]



(a) April 13, 2015



(b) April 15, 2016

Figure 1.5: Early sea-ice breakup in Beaufort Sea, Arctic [NASE]

**Alteration of Ocean-Atmosphere heat exchange** [SNa] Oceanic and atmospheric circulation try to homogenise temperatures across the globe by transporting heat from equatorial regions to polar regions. However, both mechanisms of “temperature balancing” are altered by ice melting.

On one side, ocean currents receive excessive inflows of cold fresh water. These inflows, with different salinity and density compared to ocean water, alter oceanic heat circulation (*thermohaline circulation*).

On the other side, sea ice in the poles insulates the cold polar atmosphere from the warmer ocean. This contributes to keep the poles cold, mainly in the Arctic. Nevertheless, as sea ice sheets melt down, the ocean warms more effectively the polar atmosphere and alters the atmospheric heat circulation.

As a consequence of this deterioration in global heat circulation (both oceanic

and atmospheric), climate change implies that some regions on Earth will get warmer, but some others will get cooler.

**Sea level rise** Sea levels rise mainly due to added meltwater (from land ice) and thermal expansion (higher global temperatures). Seas are rising “apparently slowly”: an average of 3.4 millimeters per year between 1993 and 2017 (24-year satellite record), which in any case doubles the average 1.5 millimeters per year between 1870 and 2000 (130-year tide-gauge record) [fSSa].

Despite these low values, we must note two things. First, sea level rises unevenly around the globe (see Figure 1.6) and equatorial Pacific islanders [Wor16] or Mauritius islanders [Hou17] are imminently at risk or already suffering its effects. Second, if this trend continued in the *long* run, millions of “climate refugees” would likely flee coastal regions (consider for example the largest, coastal megacities in the world: Tokyo, Jakarta, Manila, Shanghai, Karachi, New York City, Mumbai,...).

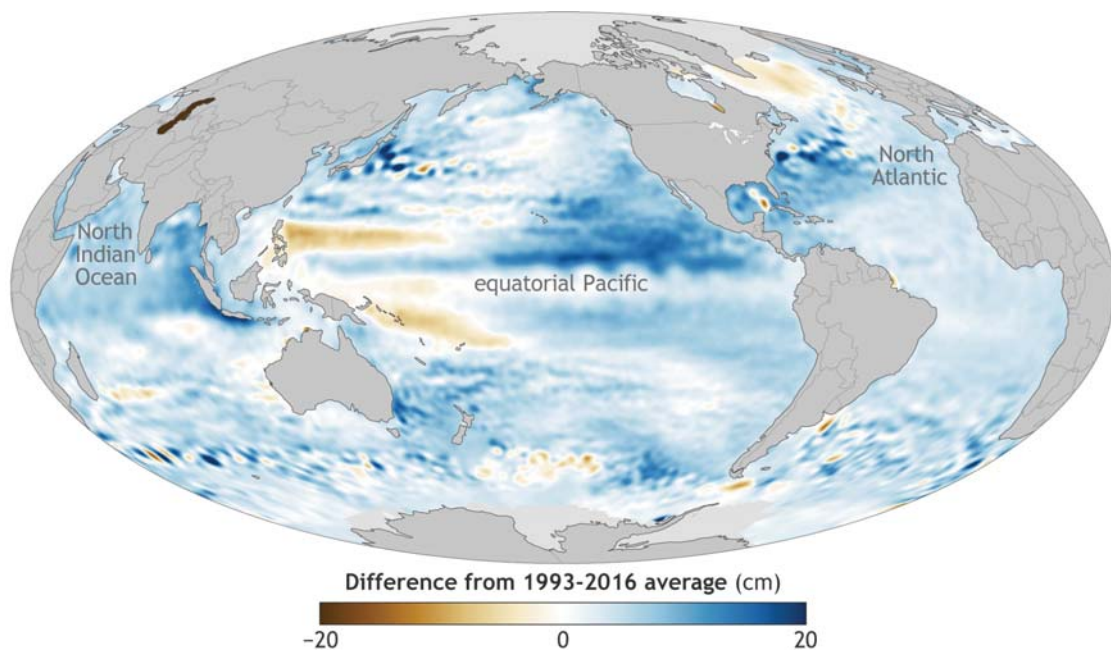


Figure 1.6: Sea level in 2016 relative to the 1993-2016 average. Credit: NOAA [Lin]

We have so far analysed four of the five key climate change indicators: global surface temperatures and the global indexes of ice and sea (Arctic sea ice minimum, land ice and sea levels). These four key climate change indicators are changing globally, although unevenly, and faster than before. What is more, these changes are self-reinforcing: for example, the higher surface temperatures are melting more ice, which leads to more heat absorbed from the Sun due to colour changes, which leads to even higher surface temperatures. However, although these environmental

processes are reinforcing one another, they are not *self-starting*. Why did they begin to change so unusually? *What destabilised them at first?* The answer lies in the fifth key climate change indicator, the CO<sub>2</sub> levels in the atmosphere.

CO<sub>2</sub> is one of the main *greenhouse gases* (GHG), together with water vapour (H<sub>2</sub>O), nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>) and chlorofluorocarbons (CFCs)[NASb]. These GHG absorb effectively the infrared heat radiating from Earth towards space and, as their concentrations increase, so does the heat “trapped” in the atmosphere. We are sure of our data: concentrations of GHG have increased over the last century. In particular, CO<sub>2</sub> concentrations have dramatically increased since the middle of the 20<sup>th</sup> century. See the trend for yourself looking at Figure 1.7. This rise in CO<sub>2</sub> concentration destabilised at first global surface temperatures and, as explained before, the other four key climate change indicators followed accordingly.



Figure 1.7: Change in atmospheric CO<sub>2</sub> concentrations in parts per million during the last 400000 years. The data combines atmospheric samples contained in ice cores and more recent direct atmospheric measurements. Credit: Vostok ice core data / J.R. Petit et al.; NOAA Mauna Loa CO<sub>2</sub> record [NASc]

We are closer to the ultimate cause of accelerated climate change. Atmospheric CO<sub>2</sub> has destabilised the other four key climate change indicators, but what destabilised atmospheric CO<sub>2</sub>? Is that simply *seasonal*? No, it does not look like seasonal at all, an abrupt change in less than a century, in a way never seen in the previous 400000 years. Which factors affecting CO<sub>2</sub> have changed so dramatically?

There is an ultimate answer: *human GHG emissions have skyrocketed, being  $\text{CO}_2$  the most significant contributor*. See it for yourself comparing the GHG concentrations in the atmosphere between 1850 and 2010 (Figure 1.8) with the human  $\text{CO}_2$  emissions in that same period (Figure 1.9). The correlation is visible and the causation is evident: atmospheric  $\text{CO}_2$  has risen dramatically because human  $\text{CO}_2$  emissions have also risen dramatically.

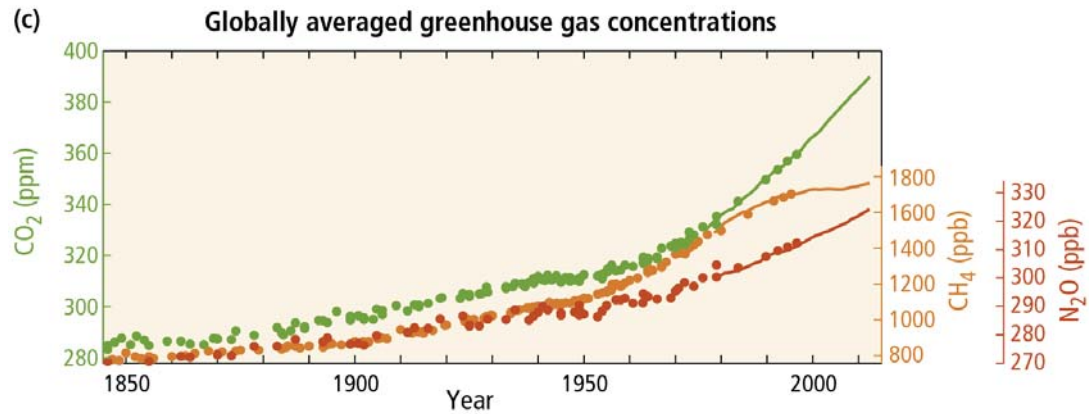


Figure 1.8: Atmospheric concentrations of the GHG. The data combines atmospheric samples contained in ice cores (dots) and more recent direct atmospheric measurements (continuous lines). Credit: IPCC [IPCC14b]

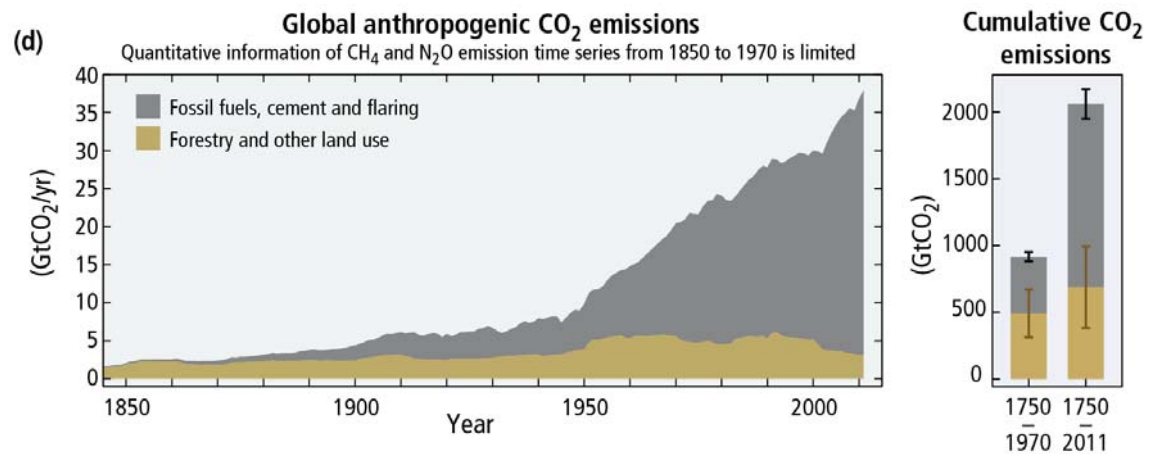


Figure 1.9: On the left side: global anthropogenic  $\text{CO}_2$  emissions from fossil-fuel combustion (including flaring), cement production, forestry and other land use. On the right side, the box plot shows cumulative emissions of  $\text{CO}_2$  from these sources and their uncertainties. Credit: IPCC [IPCC14b]

Besides the contribution of  $\text{CO}_2$ , human emissions of  $\text{N}_2\text{O}$ ,  $\text{CH}_4$  and CFCs also influence climate change. Comparing contributions of different GHG to climate

change is delicate: we have a common scale that accounts for the heat-flux behaviour of different GHG, but that does not imply equivalence of the corresponding climate change responses [MPvS14]. This common scale uses factors called “global warming potentials” (GWP), leading to a common unit, mass of CO<sub>2</sub>-equivalent. In this common scale, CO<sub>2</sub> represented around 70% and the rest of GHG around 30% of all human GHG emissions between 1970 and 2010 [IPC14b]. These relative contributions are approximate (depend on the models for GWP<sub>100</sub> and the degree of equivalent climate responses), but point in the same direction as previous analyses: *human GHG emissions have destabilised Earth’s climate, being CO<sub>2</sub> the most significant contributor.*

In a nutshell, **climate change is definitely real**. All five key climate change indicators are changing globally, although unevenly, and faster than before. Temperatures are rising, land and sea ice are melting, sea levels are rising, all triggered by rising atmospheric CO<sub>2</sub>. *“Climate change is no longer some far-off problem; it is happening here, it is happening now”*, in the words of Barack Obama [San15].

Moreover, **climate change is definitely derived from human activity**, in particular from human GHG emissions, being CO<sub>2</sub> the most significant contributor. Human activity is the destabilising agent, which it is not all bad news: if we humans are the cause, we humans can as well become the solution. But do we really have reasons to care? Is climate change such an alarming problem?

## 1.2 Is climate change an alarming problem?

*Aren’t we part of the natural world? Won’t evolution allow organisms to adapt to us and our impact on the world?*

*Well, that is the \$64 trillion question. If we were doing just one of these things, we could precipitate a mass extinction. It turns out we’re doing several at the same time. We’re not just warming the world, we’re cutting down the rain forest. We’re not just cutting down the rain forest, we’re moving invasive species into the rain forest. So you just add these all up, and you say, that’s a lot, and that’s how you get to saying: We are the asteroid now. The asteroid also had a lot of different effects, and it didn’t end too well.*

*National Geographic*

*“The Sixth Extinction: A Conversation With Elizabeth Kolbert”, [Kun14]*

Looking into the future is like walking in the fog: you can sense what is very close, you cannot imagine what is further away. Nobody could have predicted in 2004 how crude oil prices would behave in *10 years time*. Bloomberg New Energy Finance tells us that the International Energy Agency (IEA) and the US Energy Information Administration (EIA) tried. Adjusting for inflation (\$/bbl real 2000), they projected

a stable price between \$20 and \$30 per barrel. They missed it completely. Oil spot prices were almost always above \$40 per barrel and consistently above \$60 per barrel, the double of the predicted values. In addition, prices were far from stable, ranging between \$20 and \$120 per barrel [Lie17].

Nobody could have predicted in the early 1980's how many mobile phones would be in use in *20 years time*. McKinsey & Company tried and projected that the total market for mobile phones would be around 900000 [Eco99]. If you assume that “total” means “in the US”, McKinsey missed it completely: in 2000 there were more than 109 million mobile cellular subscriptions in the US. If you assume instead that “total” means “worldwide”, the prediction was even further away: in 2000 there were more than 730 million mobile cellular subscriptions worldwide (as a side note, in 2016 there were more than 7500 million) [WBMb].

What is the moral of these stories? “Future is unexpected”.

Climate change is no exception. Nobody can accurately predict how climate change will look like in *30, 60 or 90 years time*. We will nevertheless try to imagine an unmitigated climate change. The five key climate change indicators will *most probably* continue the long-term trends of rising temperatures, melting ice, rising seas and rising CO<sub>2</sub>. This in turn will *most probably* change biodiversity, agricultural patterns or precipitation patterns. At the same time, their most extreme evidences will *likely* become more common: extinctions [Kun14], redistribution of animal species [ea17b], redistribution of crops (for example, in the case of the coffee belt [Mit17] & [Lon17]) and more frequent floods, droughts and tropical storms [NASd] & [Mun17].

All these effects *might* trigger local resource competition, volatile food prices [WvB13], altered patterns of disease transmission [ea17b] or migrations. Thus, unmitigated climate change *might* become “*the ultimate “threat multiplier”: it will aggravate already fragile situations and may contribute to social upheaval and even violent conflict*” [ANe15].

Economic impacts of unmitigated climate change are largely uncertain and unevenly distributed. International organisations (such as IPCC or OECD), financial institutions [Eco15] and independent journals (such as Nature or Science) have proposed manifold scenarios.

Many estimates of economic losses are based on integrated assessment models (IAM), which try to combine the key elements of biophysical and economic systems [Ste16]. These IAM rely on many assumptions, but are *incomplete* (typically they neither account for tipping points nor for some of the largest potential impacts, such as violent conflict as a result of large-scale migrations) and are *disputable* (most current models assume that people will be much wealthier in the future and that lives in the future are less important than lives now) [Ste16].



We cannot dismiss these suboptimal models. Although they overlook potential impacts and tipping points, they reach overwhelmingly negative conclusions. We do not accurately know how climate change will behave, but chances are its economic consequences will *likely* be severe. Let's review the future economic scenarios in chronological order of publication.

In 2014, IPCC estimated “conservative impacts” if climate change was mitigated. If global surface temperatures rose no more than  $2^{\circ}\text{C}$  above pre-industrial levels, then global gross domestic product (GDP) would diminish between 0.2% and 2% [IPC14a]. One year later, in 2015, the Paris Agreement reached at COP21 mentioned the IPCC several times and set to limit the global temperature increase to “well below”  $2^{\circ}\text{C}$  above pre-industrial levels, with an effort to limit it to  $1.5^{\circ}\text{C}$  [LZ].

However, a  $2^{\circ}\text{C}$  increase is a *too optimistically* mitigated climate change. In a recent study published in Nature [RZF<sup>+</sup>17], the *likely* increase of global temperature in 2100 ranges between  $2.0^{\circ}\text{C}$  and  $4.9^{\circ}\text{C}$ , with median  $3.2^{\circ}\text{C}$ , already considering some emission mitigation policies. Even though these long-term predictions are inherently uncertain, they are relatively sure of one conclusion: there is a 95% probability of global temperature increases above or equal to  $2.0^{\circ}\text{C}$ . Thus, economic impacts will *very likely* be worse than the  $2^{\circ}\text{C}$  case proposed by IPCC and adopted by the Paris Agreement.

In November 2015, a month before the COP21 meeting in Paris, the OECD and Nature published more pessimistic scenarios than the IPCC ones, although they were less widely publicised.

On one side, OECD scenarios pointed out that an *unmitigated* climate change could reduce global GDP between 1.0% and 3.3% by 2060 and between 2% and 10% by 2100. Almost all (92%) regions in the analysis suffered negative impacts, being Africa and Asia the most harshly affected [OEC15].

On the other side, Nature endorsed even a more extreme view: “*If future adaptation mimics past adaptation, unmitigated warming is expected to reshape the global economy by reducing average global incomes roughly 23% by 2100 and widening global income inequality, relative to scenarios without climate change*” [BHM15]. This research was different from the traditional approach in two ways: it focused on economic growth (instead of on current output) and was based on historical observations (historical responses of annual economic growth to annual temperature fluctuations in 166 countries between 1960 and 2010) [Fie15].

In December 2015, a week before the COP21 meeting in Paris, The Economist summarised the stances on climate change of financial and insurance institutions. Taking one as example, Moody has rated \$9 trillion out of \$67 trillion of corporate bonds at climate change risk over the medium term (defined as more than five years

ahead). Unsurprisingly, the sectors *coal mining* and *coal terminals* faced “immediate and elevated” risk from climate change, while *oil refiners* faced “emerging, elevated risk”. Right at the end of its article, The Economist acknowledged that although all investment strategies have risks, “*ignoring the climate issue altogether looks like the biggest risk of all*” [Eco15].

Remember the words of Christiana Figueres, former secretary of the United Nations Framework Convention on Climate Change: “*Climate change increasingly poses one of the biggest long-term threats to investments*” [San15]. Investors needed higher transparency from companies on how they managed climate change risks and opportunities. In June 2017, this climate concern was addressed by the Task Force of Climate-related Financial Disclosures (TCFD). The TCFD published three documents to frame all climate-related financial disclosures and to provide detailed information on its implementation and scenario analysis [TCF17]. Over 100 companies (including several oil and mining companies) expressed their commitment to support these voluntary recommendations [TCF]. Besides, in October 2017, more than 600 big companies already used internal carbon price metrics to inform strategic decisions and around 780 more are planning to introduce them by 2019 [Cro17i].

Also in June 2017, the month when Donald Trump announced the US withdrawal from the Paris Agreement, the journal Science published estimates for the economic consequences of climate change in the US. I want to highlight two of their conclusions. First, the reduction of national wealth: an average decrease of 1.2% of GDP per  $+1^{\circ}\text{C}$ . Second, the increase of national inequality: in 2100, the richest third of counties would decrease their incomes between -1.2 and 6.8% (negative values mean increases in income), whereas the poorest third of counties would decrease their incomes between 2.0 and 19.6% [HKJR17]. Again, if climate change is not successfully mitigated, the economic damages will *very likely* be severe and unevenly distributed, even at the national scale.

In a nutshell, **climate change is definitely an alarming problem**. Global economic damages alone are shocking, but consider them together with the environmental, social and geopolitical impacts. Despite the fact that our predictions of the future are uncertain, our predictions reach overwhelmingly negative economic conclusions (global decreases of GDP, unevenly distributed) and leave other alarming questions open, such as the displacement and reduction of biodiversity, human migrations or violent conflict due to resource competition.

We have reached three conclusions so far: 1) climate change is definitely **real**, 2) climate change is definitely **derived from human activity** and 3) climate change is definitely **an alarming problem**. These conclusions are far from pleasing, but there is room for hope. If we humans have triggered the problem, can we humans put the means in place to solve it? What can we do to alleviate climate change?



### 1.3 What can we do to alleviate climate change?

We previously concluded that human activity is the destabilising agent of climate change through human GHG emissions, being CO<sub>2</sub> the most significant contributor.

Fortunately, global CO<sub>2</sub> emissions stalled between 2014 and 2016 [UNE17] & [JRC16], but the trend is reversing and global GHG emissions will break records in 2017 [BH17]. Unfortunately, *current emissions* of CO<sub>2</sub> are only a fraction of the issue, what really matters are *cumulative emissions* of CO<sub>2</sub>. The reason is the residence time of CO<sub>2</sub> in the atmosphere: the IPCC 2013 assessed that between 15% and 40% of all CO<sub>2</sub> emissions until 2100 will remain in the atmosphere more than 1000 years [IPC13]. An alternative reading of that science is: climate change *today* is caused by all CO<sub>2</sub> since the start of the Industrial Revolution and climate change *several centuries into the future* will *still* be caused by all CO<sub>2</sub> since the start of the Industrial Revolution. We cannot rewind time to prevent past CO<sub>2</sub> emissions.

Forests and other ecosystems can absorb already-emitted CO<sub>2</sub> and partially offset emissions, such as in the US [141]. However, land use, land-use change and forestry are currently net emitters of CO<sub>2</sub> on the global scale [IEA17c]. Besides, negative-CO<sub>2</sub> technologies (such as direct air capture, afforestation or bioenergy with carbon capture and storage) might scale in the future, but we cannot predict when. For the time being, neither natural ecosystems nor human technologies can absorb already-emitted CO<sub>2</sub> at the scale required by the urgency and severity of the problem, even though 101 out of the 116 IPCC models assume “negative emissions” in the financially optimal paths to achieve the Paris Agreement’s targets [Bri17].

At this time, this is our silver bullet: curbing future CO<sub>2</sub> emissions. If we curb them, future rise in average global temperature will curb as well, because there is an almost linear correlation between rise in average global temperature and atmospheric concentration of CO<sub>2</sub>. At this point, the concept of “CO<sub>2</sub> budget” arises: we can associate the remaining CO<sub>2</sub> that can be emitted over a period with a probability of reaching a chosen rise in average global temperature over that period [IEA17c].

The International Renewable Energy Agency (IRENA) and IEA calculated the CO<sub>2</sub> budget for the temperature objectives of the Paris Agreement. IRENA’s and IEA’s scenario limit the rise in average global temperatures to 2°C (with a probability of 66%) throughout the 21<sup>st</sup> century, without any temporary overshoots. They do account for the influence of land use, forestry and non-CO<sub>2</sub> emissions (which stem mainly from agriculture and waste), but do not account for negative-CO<sub>2</sub> technologies that *might* scale in the future. In this scenario, IRENA and IEA calculated a CO<sub>2</sub> budget of 880 Gigatons (Gt) between 2015 and 2100 [IEA17c]. This value lies in the middle of the (590 Gt, 1240 Gt) interval proposed by a different analysis that targeted the same temperature rise with the same probability [ea16].

How can we allocate this CO<sub>2</sub> budget among all emitters in the economy? Currently, the largest CO<sub>2</sub> (and GHG) emitter is the energy sector. Adjusting for GWP<sub>100</sub> values, energy-related emissions (almost entirely CO<sub>2</sub>) account for 2/3 of all human GHG emissions [IEA16b]. These values are far larger than the next largest contributions: agriculture ( $\approx 11\%$  of human GHG emissions, mainly attributable to CH<sub>4</sub> and N<sub>2</sub>O [140]) and non-energy industrial emissions ( $\approx 7\%$ , with a significant contribution of CO<sub>2</sub> from calcination in cement production [Rub12] & [IEA17c]).

IRENA and IEA account for this “supremacy” of energy-related CO<sub>2</sub> emissions and allocated almost 90% of the total CO<sub>2</sub> budget to it, 790 Gt between 2015 and 2100. In parallel, the Energy Transitions Commission (ETC) allocated an even higher CO<sub>2</sub> budget for the energy sector: 900 Gt between 2017 and 2100 [ETC17].

What exactly do we mean with “energy sector”? The energy sector is virtually everywhere, because it encompasses all emissions from *fuel combustion* and other *fugitive emissions* (mainly externalities from the lifecycle of fuels before their combustion). Energy-related emissions are therefore present in electricity generation ( $\approx 50\%$  of all energy-related CO<sub>2</sub> emissions in the mid 2010’s), in transport ( $\approx 20\%$ ), in industry ( $\approx 20\%$ ) and in buildings ( $\approx 10\%$ ) [IEA17c].

The large majority of energy-related emissions stem from fuel combustion [IEA16b]. More in particular, they stem from *fossil fuel combustion* (more than 99% of all fuel-combustion emissions in 2015): from coal ( $\approx 45\%$ ), from oil ( $\approx 35\%$ ) and from natural gas ( $\approx 20\%$ ) [IEA17b]. These fossil fuels are however the backbone of our energy system: worldwide in 2015, fossil fuels represented 4/5 of primary energy supply and 4/5 of final energy consumption (accounting for their electricity contribution) [IEA17b]. In other words, whenever you “see” energy, you are most probably seeing fossil fuels and their related emissions.

The transformation of the energy sector, known as *energy transition*, is hence at the core of climate change mitigation. It is a global challenge (how will our economies use enough energy to deliver shared prosperity with much reduced CO<sub>2</sub> emissions? [TdPM17]) with manifold geographical approaches.

To tackle this global challenge, the World Energy Council provides a conceptual framework, the “Energy Trilemma”, based on 3 core dimensions: 1) *energy security* (energy is always available when needed), 2) *energy equity* (energy is accessible and affordable) and 3) *environmental sustainability* (energy is produced and consumed in an efficient and clean way) [Cou]. We will develop these core dimensions and define the energy transition as a *transition in energy quantity and energy quality*.

On one hand, it is a transition in the *energy quantity*. Quite recently, in the mid 2010’s, the energy use per capita in high-income countries was on average 2.1 times the value for upper-middle-income countries and 7.4 times the value for

lower-middle-income countries [WBMa]. There is not even data to compare with the low-income countries [WBL]. Despite this gap, some values seem to slightly converge (see the trend for yourself in Figure 1.10). Ideally, the energy transition should accelerate the convergence of all these values.

Therefore, some countries should reduce their energy consumption and become significantly more efficient, especially the high-income countries, whereas some countries should increase their energy consumption to raise their standards of living, especially the low-and-middle-income countries. Some will focus on *efficiency*, for example shifting their economies to “circular” paradigms (closed loop supply chains with almost complete recycling) and “sharing” paradigms (using without owning, such as with vehicles) or promoting denser urban designs [ETC17]. Some will focus on *accessibility*, for example promoting both centralised and decentralised electricity growth, *as well as on efficiency*.

Do not forget efficiency in any case. Not even in developing economies, since typically they have more energy-intensive industries and use less efficient energy technologies in all their economic sectors. For example, in India and China, energy efficiency potentially contributes the most to CO<sub>2</sub> emission reductions, raising living standards with slower energy demand growth [IRE17b].

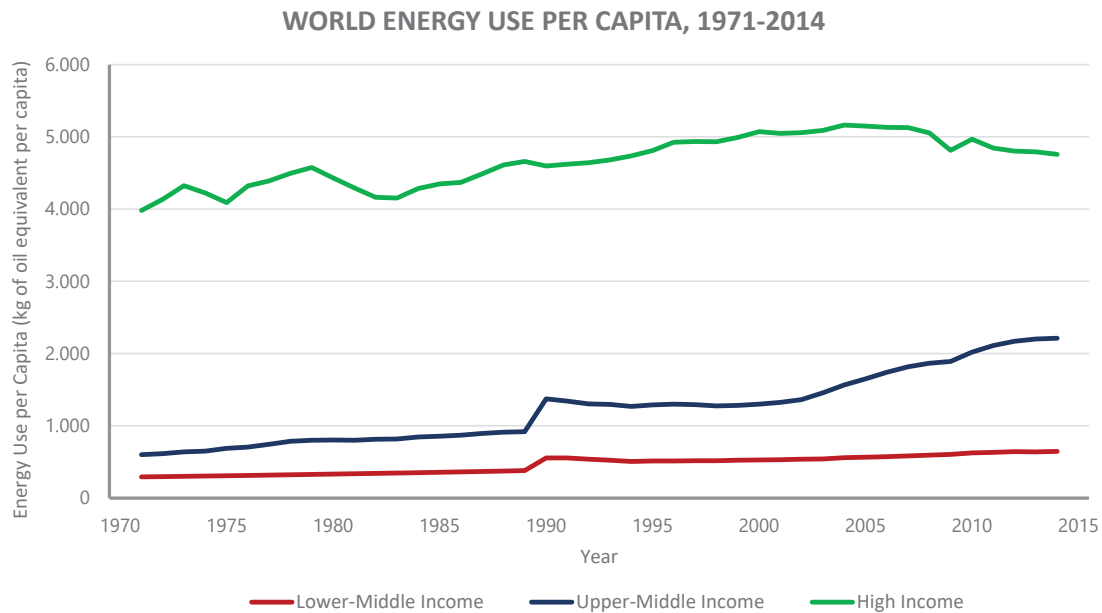


Figure 1.10: Average energy use per capita (kg of oil equivalent per capita) for lower-middle-income, upper-middle-income and high-income countries between 1971 and 2014. Data from The World Bank [WBMa]. There is no data available for low-income countries [WBL]

On the other hand, it is a transition in the *energy quality*. We want our energy to be 1) clean, 2) reliable and 3) affordable and the three words are equally important [aD]. How do we assess our current energy system in these three dimensions?

Currently fossil fuels are the backbone of our energy system (4/5 of primary energy supply, 4/5 of final energy consumption) and the means of international energy flows (almost 1/2 of crude oil, 1/4 of natural gas and 1/6 of coal are exported internationally compared to less than 1/50 of electricity [IEA17b]). They are rather *reliable*: even though they are hugely imported, they support a diversified and dispatchable energy portfolio in primary energy supply and electricity generation. They are rather *affordable*, especially coal, and therefore it is no surprise that middle-income countries such as Brazil, India and China have increased their coal consumption by 140%, 425% and 514% respectively since the 1980's (China and India were low-income countries back then) [Spo17a] & [Banc]. However, fossil fuels are *far from clean* in terms of CO<sub>2</sub> emissions, especially coal.

How could we sustain the reliability and affordability of the energy system while turning it cleaner? How could we sustainably decarbonise our economy? The most promising strategy is twofold: *clean the consumption, clean the generation*.

On one side, we can decarbonise the consumption points, where final energy (such as gasoline, charcoal or electricity) is transformed into useful energy (such as mechanical energy, heat or lighting). Here the most promising lever is extended electrification, since electricity is always clean at the point of consumption. “Electrify the economy” as much as possible, focusing first on light vehicle transport and building heat services [ETC17].

However, there are activities that cannot be easily, cost-effectively electrified, such as long-haul transport or some industrial applications (steel, cement or chemicals production [ETC17]). These activities may not be cost-effectively electrified, but should anyway be cost-effectively decarbonised. We can decarbonise them by substituting their fuel (transitioning towards biofuels, hydrogen or at least from coal to natural gas) or by partially avoiding their CO<sub>2</sub> emissions through Carbon Capture and Storage (CCS). These cleaner, newly-built industrial systems will come at an additional CapEx, but they have long lifetimes (of over 30 and 40 years [TdPM17]) to pay it off. Already-built industrial systems should ideally pay them off faster.

On the other side, we can decarbonise the generation points, specifically where primary energy (such as wind) is transformed into secondary energy (such as electricity). We will focus on electrical secondary energy, which is evidently coherent with the trend of extended electrification: *we want more electricity, because it is clean at consumption, but electricity must also be clean at generation*. With that in mind, we should maximise the zero-carbon electricity sources (mostly renewables) while minimising the most-emitting ones (mostly coal-fired generation).

Fortunately, environmental progress can nowadays arise from economic rationale: there is a collapsing price of renewable energy from solar photovoltaics (solar PV) and wind (mainly onshore, but also offshore) [TdPM17]. Bloomberg New Energy Finance shows this collapsing trend of prices over time [Lie17]. Renewables are becoming affordable, that is a fact today. If we combined this fact with two promises (the sought-after carbon taxes [aD] and the booming energy storage [IRE17a]), renewables could be as reliable and affordable as fossil fuels. However, until those promises become facts, we will still need certain subsidies and back-up technologies.

Besides these main initiatives (*clean the consumption, clean the generation*), there are other energy-related initiatives that could contribute to a lesser extent. One example is the “Zero Routine Flaring by 2030”, introduced by The World Bank, that aims to eliminate by 2030 all natural gas flaring during crude oil extraction [Band]. Currently, flaring wastes  $\approx 4\%$  of all natural gas production [Banb] & [IEA17b]. It may sound negligible, but if this natural gas was used instead for electricity generation, it could provide more than Africa’s current annual electricity consumption [Band].

Nowadays, G20 countries are pioneering the energy decarbonisation. They are cleaning the generation (G20 holds 98% of global wind capacity, 96% of solar PV capacity and 94% of nuclear power capacity) and cleaning the consumption (G20 holds 95% of all electric vehicles worldwide) [IEA17c]. Nevertheless, remember that the energy transition goes beyond the energy decarbonisation. In one sentence, the energy transition entails that *“we will have to really very significantly move away from fossil fuels, while still delivering in many countries even more energy use than there is today”*, in the words of Lord Adair Turner [TdPM17].

If this transition is to come true, new policies must partner with new investment. On the policy side, measures should phase out fossil-fuel subsidies, rise CO<sub>2</sub> prices to unprecedented levels, promote efficiency and electrification and reform extensively the energy market. On the financial side, IEA and IRENA estimated how much the global economy should *ideally* invest in new energy technologies between 2016 and 2050: IEA estimated \$3.5 trillion on average per year, whereas IRENA estimated \$4.1 trillion on average per year [IEA17c]. They also detailed how these investments should *ideally* be allocated. These *ideal* annual investments represent between 4.5% and 5.3% of annual global GDP (in 2016 [Bana]) and will diminish in the future as annual global GDP increases.

As you see, this transition will go beyond the energy sector: it will shake economies up. It will go hand in hand with an industrial and economic transition away from the ways goods and energy are being produced and from the ways goods and people are being transported. Additionally, it will deliver social benefits, such as improved local air quality (leading to longer and healthier lives). And, of course, it will dramatically mitigate climate change.

The Paris Agreement was a step forward for the energy transition, but is nowhere near enough to where we should be. IEA and IRENA analysed the Nationally Determined Contributions (NDCs) submitted under the Paris Agreement and their findings were disheartening. If all countries abided by their promises, the “transformed” energy sector would emit until 2050 nearly 60% more than the allowed CO<sub>2</sub> budget until 2100 [IEA17c]. We urgently need to accelerate the energy transition. We. Urgently.

What makes matters worse is that recent policies are blowing hot and cold. France [Sto17], the UK [PC17] and maybe even China [Clo17] are planning to ban fossil-fueled cars in the near future, while however fossil fuel subsidies still accounted for 6.5% of global GDP in 2015 [CPSS17]. China piloted seven regional carbon exchanges and is planning to launch a nationwide trading system [XSR17] & [Kyn17], while however the US is withdrawing from the Paris Agreement [SJC17a]. What is more, energy investments are also lagging behind: \$1.9 trillion in 2015 and \$1.7 trillion in 2016, around or even less than half the ideal figures [Eneb].

In a nutshell, the energy sector (lifecycle emissions of fuels, mainly combustion emissions) accounts for 2/3 of all human GHG emissions, being fossil fuels the most significant contributors: coal, oil and natural gas. Accordingly, **the transformation of our energy sector, known as energy transition, is at the core of climate change mitigation**. On one hand, it is a transition in *energy quantity* (accessible and efficient): some countries will consume less and some will consume more, while all should enhance energy efficiency. On the other hand, it is a transition in *energy quality* (clean, reliable, affordable): shift from fossil fuels towards cleaner energy sources and electrify final energy consumption.

**The direction for the energy transition is no longer the problem. The problem now is its urgency.** Christiana Figueres acknowledged that issue: “The question for me is not the direction, but the speed and the scale [...] We need to be at the maximum of global emissions of GHG by 2020 [...] that sounds practically impossible [...] The question is: how are we going to make it achievable?” [aD]. How could that be? Why is the energy transition, our best solution to mitigate climate change, so clear in theory and so messy in practice?

*Angela Merkel told the UN climate change conference in Bonn on Wednesday that global warming was the “central challenge of mankind”. But she warned that countries were on track to miss the goal set out in the 2015 Paris Agreement to keep the rise in global temperatures to below 2°C from the pre-industrial age.*

*“We know the Paris agreement is a starting point”, the German chancellor said. “We also know that with the national commitments made so far we will not reach the 2°C goal.”*

*Financial Times*

*“France and Germany call for greater effort to curb climate change”, [Buc17b]*

## Chapter 2

# The Wild West: “The Good, the Bad and the Ugly”

*“You see, in this world there’s two kinds of people, my friend: those with loaded guns and those who dig. You dig”,* the good told the ugly. The ugly certainly understood that he had no other option: he obediently dug and finally unearthed the treasure. The following scene is a mix of feelings: the good shares half of the treasure with the ugly, while at the same time leaves him hanging, on the verge of death. The ugly starts to yell the name of the good and, whoever knows why, the good forgives him and abandons him with half of the treasure. In a burst of hatred, the ugly effusively curses the good, as the good disappears in the distance, at the sound of the most famous theme of “The Good, the Bad and the Ugly”. The End.

These are the final scenes of the western film “The Good, the Bad and the Ugly”, which tells us the adventures of these three characters looking for the same treasure in the American Southwest, during the American Civil War. The good is a bounty hunter, the bad is a mercenary, the ugly is an outlaw. This trio depicts a war inside a war: they are in their own small war, always changing alliances and betraying each other in the pursuit of the treasure, while often encountering the bigger, American Civil War.

Despite their betrayals, their bond is unwillingly unbreakable, because they need each other to finally find the treasure in a graveyard. The ugly knows the name of the graveyard, but the good knows the name of the tomb where it is buried, forcing them to “collaborate”. In parallel, the bad is relentlessly chasing the treasure as well, fleetingly cooperating with the good and with the ugly, although the bad eventually dies in a puzzling gun duel. As you see, there are alliances and betrayals, gold and gun duels, desert and dust. Welcome to the Wild West.



Figure 2.1: From top to bottom, the good (Clint Eastwood), the ugly (Eli Wallach) and the bad (Lee Van Cleef). Image from UniInfoNews [Goo]

## 2.1 The energy war inside the climate war

You might be wondering why I am telling you this story. The reason is simple: it resembles the smaller war of the energy transition inside the bigger war of climate change. Having said that, you know that no two stories are the same, they always have differences and similarities.

The energy war has far-reaching consequences inside the climate war, far more decisive than the influence of the good, the bad and the ugly in the American Civil War. Now, the outcomes of the smaller war on energy will largely determine the outcomes of the bigger war on climate change. Additionally, this time the smaller war has a substantially larger treasure than in the Wild West. It goes beyond gold (ideally between \$3.5 trillion and \$4.1 trillion on average each year between 2016 and 2050) and entails the success or failure in the mitigation of climate change (an alarming problem with likely severe environmental, economic and social damages).



Strikingly, the energy war stars its genuine trio of good, bad and ugly characters. I will describe them in detail in the following pages. Unlike in the Wild West, you will see that they are not as cooperative as they should be to unearth the treasure. They are just fighting against each other and, further down the road, this would have tragical consequences. The good and the ugly would not unearth the treasure, because they did not collaborate. Meanwhile, the bad would close in. This will be one of our takeaways: as in the Wild West, the good alone cannot defeat the bad in time. The ugly might have something to say in this energy transition.

Let me start introducing the genuine trio of characters. Let me start with “*the good*”, *the new clean and renewable energy technologies*. They are making many headlines and you surely know them well: the *new* wave of renewables (starring mainly solar PV, onshore wind and recently offshore wind), the *new* energy storage or the *new* electric vehicles. They are cleaning the consumption points as well as the generation points at costs declining day by day. They are widely acclaimed and are attracting noticeable investments:  $\approx$  \$300 billion for renewable generation in 2016, almost 40% of all electricity investments in 2016 [Eneb], but still far below IRENA’s ideal  $\approx$  \$700 billion per year between 2016 and 2050 [IEA17c].

Fortunately for the energy transition, renewable energy technologies as a whole are “united”, pushing in the same direction. Besides, they have surged compared to other energy sources: world final energy consumption from wind, solar and other non-hydro renewables has grown more than 1200% since 1990 [Cla17a]. Unfortunately, renewable energy technologies as a whole represented less than 1/5 of final energy consumption in the mid 2010’s [WBRd] and were primarily led by bioenergy (in particular, by fuelwood [WEC16a]) and secondarily by hydropower. Tomorrow might be the day of wind and sunlight, but today is the day of wood and water.

Let me continue with “*the bad*”, *the fossil fuels*. They are making miscellaneous headlines, ranging from the multidirectional strategies of Oil & Gas companies (shifting from oil towards natural gas, diversifying or going public) to the uncertain future of coal. Fossil fuels are the only energy technologies attracting more investments than the ideal figures: around \$800 billion in 2016, although decreasing since 2014 [Eneb], compared to IRENA’s ideal figure of around \$600 billion [IEA17c].

On one side, remember that fossil fuels are affordable and reliable, but they are far from clean. That makes them “the bad” for this energy transition inside the bigger picture of climate change. On the other side, remember that they are the backbone of our energy system (4/5 of primary energy supply, 4/5 of final energy consumption) and the means of international energy flows. That makes them very powerful to halt the pace of the energy transition.

Fortunately for the energy transition, fossil fuels are “divided”, fighting against each other. Unfortunately, they are receiving trillions in subsidies (6.5% of global

GDP in 2015) and want time to shift their core businesses, but we cannot afford to give away more time. *We know the direction, the problem now is the urgency.*

What are you missing? What seems relatively out of the discussion until now? That is precisely “the ugly” of the energy transition. *“The ugly”, the forgotten solutions, such as energy demand measures or nuclear energy.* They are not making so many promising headlines lately and they are forgotten in many senses. This oblivion is most worryingly reflected in the minimal share of investments.

First, energy demand measures (mainly energy efficiency and fuel switching) are attracting only 1/8 of all energy investments (and this share even includes EVs) when they should ideally be the largest share of all. Verify it for yourself in Figure 2.2. IRENA’s ideal investments should be more than \$2.1 trillion each year between 2016 and 2050 [IEA17c], whereas the actual investments are scarcely \$250 billion [Eneb]. IEA’s ideal investments in energy efficiency are also “challenging” compared to the actual figures, starting at approximately \$600 billion per year between 2016 and 2020 and reaching the \$2.7 trillion per year between 2041 and 2050 [IEA17c].

Second, nuclear energy saw in 2016 the largest gross capacity additions since 1990 (and largest net capacity additions since 1993 [Age17]), but that value is still half of the 2DS targets (2.0°C increase by 2100 with 50% probability) [IEA17d] & [IEA17d]. We will later discuss the ideal investments in nuclear energy, because are at the very least *unclear* in the scenarios analysed by IEA and IRENA.

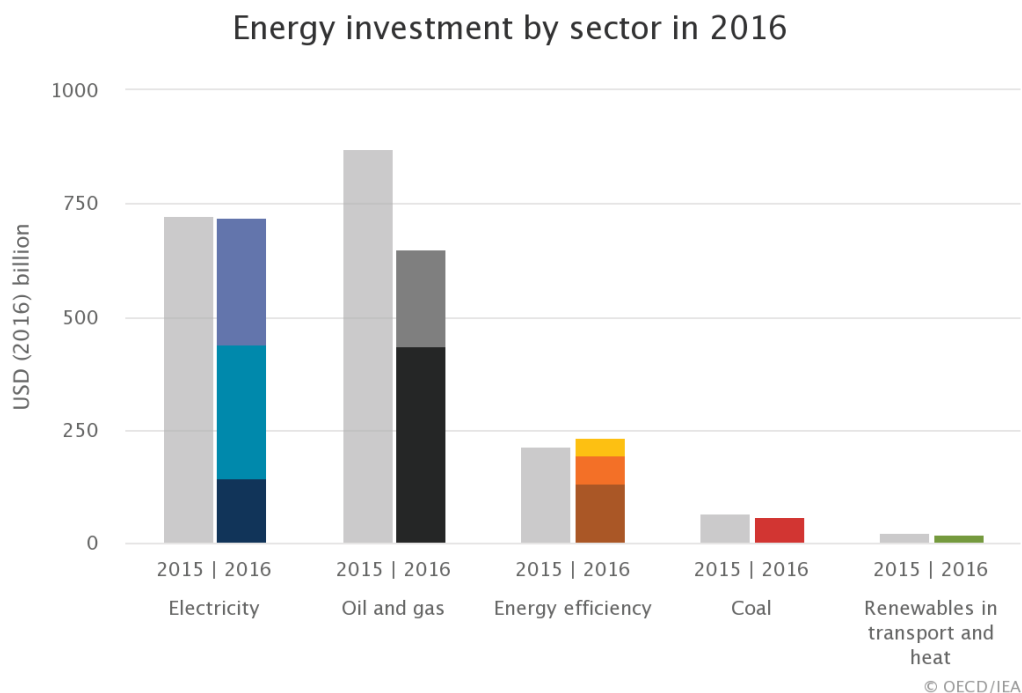


Figure 2.2: Energy investments by sector in 2016. Credit: OECD and IEA [Eneb]

Lastly, let's compare all the previously-mentioned investments in energy supply in Figure 2.3. We know that unexpected technological advances, political reforms or different discount rates could partly explain the investment gaps between actual and ideal values. Nevertheless, in any case these huge gaps speak for themselves: fossil fuels are still too powerful, renewables are lagging behind and other technologies (such as nuclear energy or energy efficiency measures) are being dismissed.

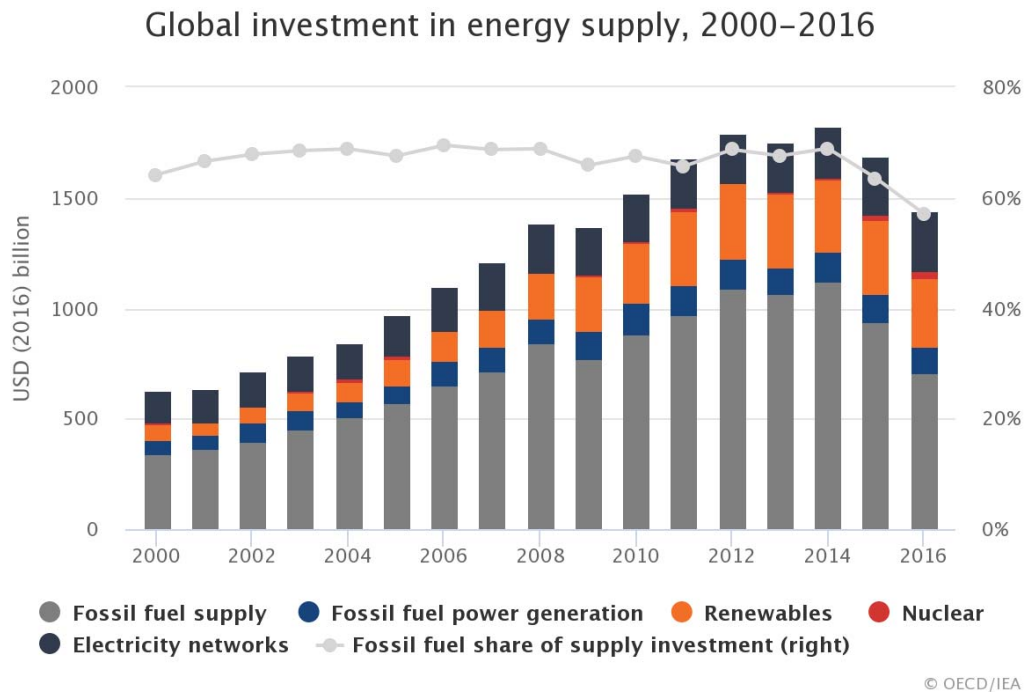


Figure 2.3: Energy investments in energy supply by technology. “Renewables” include *here* renewable electricity, transport and heat. Credit: OECD and IEA [Eneb]

In short, the smaller war of the energy transition inside the bigger war of climate change resembles the western film **“The Good, the Bad and the Ugly”**. In the energy transition, “the good” are the popular clean energy technologies (wind and solar energy, energy storage and electric vehicles), “the bad” are the fossil fuels and “the ugly” are the forgotten technologies (such as energy demand measures and nuclear energy). The good are united but underinvested, the bad are divided but overinvested, the ugly are largely forgotten and largely underinvested.

As in the Wild West, **the good alone may not be able to defeat the bad**: the energy transition has a clear direction, but its urgency is compromised. McKinsey & Company agrees: *“Wind, solar and geothermal energy are growing rapidly, but the world will also continue to rely on fossil fuel for decades to come”* [NM16]. Will this forecast come true or could the good alone defeat the bad in time?

## 2.2 Could the good alone defeat the bad in time?

*During the World Economic Forum Annual Meeting 2012 in Davos-Klosters, Switzerland, executives of the world’s largest energy companies, policy-makers and thought leaders from across the energy value chain were asked: To what extent do you expect global energy systems to change over the next ten years? An overwhelming 90% expressed the belief that significant change would occur across energy architectures around the world, and nearly one-third predicted a radical shift in the way energy is sourced, transformed and consumed.*

*World Economic Forum*

*“Global Energy Architecture Performance Index Report 2017”, [WEF17b]*

*Saudi Aramco and Royal Dutch Shell acknowledged that a shift towards renewable energy — including battery-powered cars — was under way but said oil and gas would remain indispensable for decades to come.*

*“There seems to be a growing belief that the world can prematurely disengage from proven and reliable energy sources like oil and gas, on the mistaken assumption that alternatives will be rapidly deployed,” Amin Nasser [CEO] of Saudi Aramco told an energy conference in Istanbul.*

*Addressing the same event, Ben van Beurden [CEO] of Shell said the transition to low-carbon technologies would “take place over generations” rather than as a rapid “revolution”. [...]*

*Replacing fossil fuels would take at least as long as the 80 years or more it took coal and oil to establish themselves in the past two centuries, Mr Nasser said. Even as oil and gas lose market share, absolute demand would increase “for a long period of time”, he added.*

*Financial Times*

*“Big oil dismisses predictions of collapse in demand”, [War17b]*

Disheartening or hopeless, how would you describe your feelings after these statements? *The transition to low-carbon technologies would “take place over generations” rather than as a rapid “revolution”.* Wasn’t that “rapid revolution” our best chance to mitigate climate change? Theoretically it looked so utopian, but so clear, and in practice it looks so dystopian, so messy... Could we find hope in the latest news concerning the good, the clean energy technologies?

Aren’t we *cleaning the generation*? Aren’t new renewable energies immensely expanding? That is undeniably true: the world final energy consumption from wind, solar and other non-hydro renewables increased more than 1200% between 1990 and 2016. Renewable energy technologies are gaining momentum in absolute terms and accounted for more than half the new electricity generation capacity added worldwide in 2015 and 2016 [Cla17a]. In parallel, energy storage is developing rapidly: larger and larger battery storage facilities are online [Ran17] and even larger are promised [San17] while prices have been diminishing for years [Ran17].

Unfortunately, these hopeful news are irrelevant on the global stage. The UK went one full day of electricity without coal for the first time since 1882 [Cla17c], but coal is still the largest, global electricity source by far. Non-hydro renewables are a *minor fraction inside a minor fraction*: in 2015, non-hydro renewables generated just 7% of global electricity (compared to 66% generated by fossil fuels) and in turn global electricity accounted for less than 1/5 of global final energy consumption. In particular, the joint contributions of wind and solar PV were merely 1% of global final energy consumption, compared to the almost 80% of fossil fuels [IEA17b].

See the trend for yourself looking at Figure 2.4, that shows how all possible energy sources contribute to the world final energy consumption. We have normalised all values with respect to the world contribution of solar electricity.

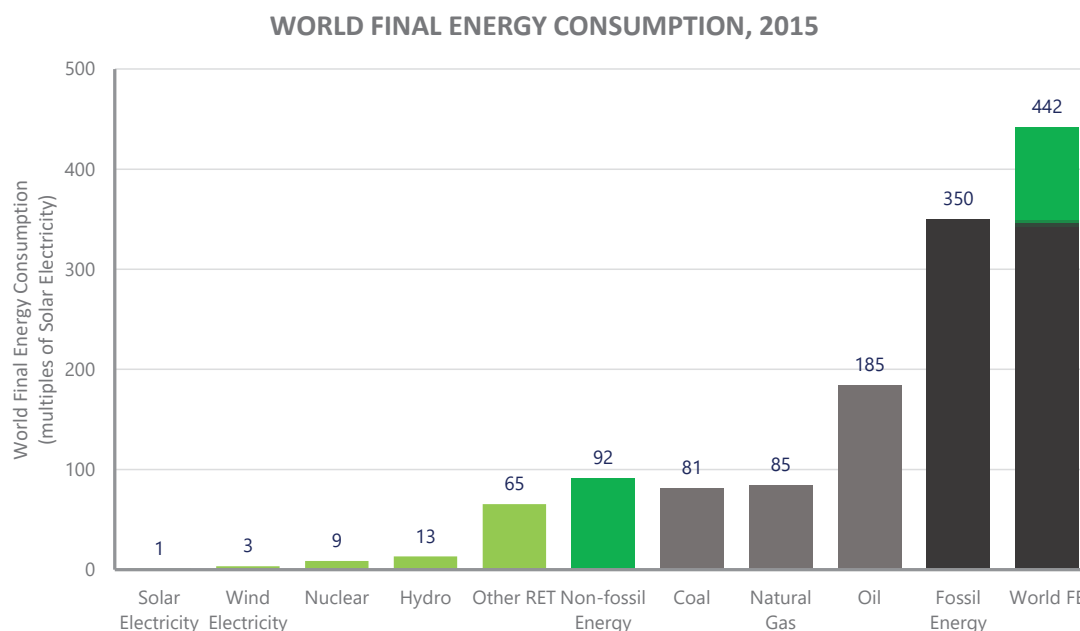


Figure 2.4: World final energy consumption in 2015 in multiples of final energy coming from solar electricity. “Other RET” includes all Renewable Energy Technologies not included in the previous categories (most importantly, biofuels and waste). “World FE” refers to World Final Energy Consumption, approximately 100 times larger than solar and wind electricity together. Data from IEA [IEA17b]

In the near future, wind and solar are unanimously projected to grow, reaching significant shares of electricity production between the mid 2030’s and 2040: 11% according to EIA [EIA17b], 15% according to ExxonMobil [EXX17], nearly 20% according to BP [BPO17] or even 34% in the energy outlook proposed by Bloomberg New Energy Finance [BNE17b]. This last figure is the only one that meets the most largely decarbonised scenarios in the electricity sector proposed by IEA (“450

Scenario” and “66% 2.0°C Scenario”), which need wind and solar PV to contribute to electricity generation slightly less than 30% (“450 Scenario”, [IEA16f]) and slightly more than 30% (“66% 2.0°C Scenario”, [IEA17c]).

Wind and solar PV *might* reach these most optimistic contributions ( $\approx 30\%$  of global electricity), but we would *likely* fail in the electricity sector as a whole: 95% of all electricity sources should be low-carbon by 2050 [IEA17c], but no other generation technologies (apart from onshore wind and PV) are reaching their 2DS target contributions [IEA17d].

And what about energy storage? It is one of the only 3 energy technologies on track with the 2DS targets. It is currently dominated by pumped-storage hydro, which represented around 96% of global installed power capacity in 2016 [DOE]. Pumped-storage hydro is expected to still dominate electricity storage by 2030, although with a very significant growth in battery storage (reaching more than 300 times its installed capacity in 2014), whose costs are expected to further diminish [IRE17a]. However, large-scale battery storage is still nascent, able to store only a few seconds of global electricity demand [Cla17a] and we will have to wait to reassure the rather optimistic predictions (that 30000% growth).

Aren’t we *cleaning the consumption* as well? Don’t we come across more electric vehicles lately? That is undeniably true: electric vehicle (EV) sales are breaking records. 750000 new EVs were sold worldwide in 2016, up  $\approx 40\%$  from the previous year [Eneb], and the ascending trend consolidates in 2017, with worldwide sales exceeding 100000 EVs several months and gaining momentum towards the second part of the year [SH17].

In parallel, the role of less advanced economies in EV expansion is still to be defined. Some argue that they might directly leapfrog to EVs, especially if China dominates the battery manufacturing in the foreseeable future and drives its costs down in the same way that it did with solar panels. Others argue that less advanced economies cannot simply switch to EVs because they have neither the electrical infrastructure nor the wealth to do so [War17i]. Further critics point to an imbalance between the environmental benefits to developed markets and the social and environmental damages to the developing world where cobalt, lithium and other critical materials for batteries are mined [Cro17d]. We will have to wait to confirm the sustainable role of less advanced economies in EV expansion, but if it was eventually confirmed, EV development would further accelerate.

Unfortunately, these hopeful news are irrelevant on the global stage. Nowadays, electric vehicles account for less than 0.2% of the 1.2 billion vehicles on the streets [War17b] and the record 750000 EVs sold in 2016 will only reduce transport oil demand by 0.02% [Eneb]. Looking into the future, BP acknowledges that EVs will inevitable rise, but conventional cars would continue to dominate the global

market for decades. In the words of Bob Dudley, BP’s CEO: “*We have forecasted that 100 million EVs will be on the road by 2035. Even if you doubled that to 200 millions, there would still be 2 billion conventional vehicles on the road*”. Goldman Sachs reached recently very similar conclusions [War17i].

What a heavy blow to our expectations. The bad’s supremacy dwarfs any hopeful headlines about the good, now and for the coming decades. **The good alone cannot succeed in time, the bad will impose their slower pace**. It seems that now, as in the Wild West, it is time to forge alliances. Maybe the good cannot win alone, but can win after all. Who could collaborate with the good?

*Advanced energy acceleration would “let a hundred flowers bloom” at once. Successive US administrations have adopted an “all of the above” policy on energy technologies, and emerging economies like China and India have predicated their economic development plans on a full menu of fossil, nuclear and renewable energy sources – partly because no one energy source can supply the full magnitude of need without also compromising other priorities like affordability or public health and environment [...] The 21<sup>st</sup>-century economy could depend, at least initially, on a range of nearly 15 to 20 different technologies.*

*World Economic Forum, McKinsey & Company*

*“Game Changers in the Energy System - Emerging Themes Reshaping the Energy Landscape”, [WEF17a]*

## 2.3 Could the *bad* reach out to the good?

The answer is surprisingly “yes”, because the bad are internally divided. Oil & Gas companies could become unexpected allies of the good, because they 1) are *shifting from oil towards natural gas*, a cleaner and more efficient energy source, 2) are *fighting coal*, the most polluting fossil fuel, and 3) are *diversifying into green technologies*, hedging climate concerns in an attempt to become “beyond-fossil energy companies”.

### 2.3.1 Shifting from oil towards natural gas

First, Oil & Gas companies are shifting their core business from oil towards natural gas. This shift makes all the environmental sense, since natural gas is the least contaminant of fossil fuels and can be burnt more efficiently: “*The largest contribution Shell can make to reducing emissions globally in the near term, is to continue to grow the role of natural gas*”, in the words of Ben van Beurden, Shell’s CEO [vB17].

Shifting from oil towards natural gas also makes all the financial sense, since the number of countries importing liquefied natural gas (LNG) has almost doubled in the past decade [War17a] and it will play an increasingly important role in the coming decades [BPO17]. Bloomberg New Energy Finance agrees with this projection [Lie17]. Claudio Descalzi, Eni’s CEO, agrees too: “*In the past, when you struck gas rather than oil in this industry you were disappointed, but now we go looking for it*” [War17a].

LNG is growing swiftly, on course to increase supply by 50% between 2014 and 2021, which implies that a new LNG “train” comes online every two or three months. ExxonMobil and Shell are currently leading the LNG way, closely followed by BP [War17a], which is pushing hard to catch up: in 2017, 6 of the 7 seven BP’s major projects are natural gas projects and, between 2017 and 2020, BP is projected to see the greatest growth in gas production of all the supermajors as new projects come onstream [BPG].

BP is the most visible exponent of an industry-wide strategy. Natural gas outweighs oil by a factor of two-to-one among pre-development resources awaiting investment decisions [War17a] and Bloomberg New Energy Finance expects that 26 LNG new projects will come online between 2017Q1 and 2020Q1 [BNE17a]. Oil & Gas companies are not only investing in well-known onshore gas technologies, mainly to develop US’ shale gas [Cro17a] and Australia [Smy16b], but also in innovative floating LNG platforms [Smy17b]. Nonetheless, financing these natural gas investments becomes a challenge for Oil & Gas companies in an era of \$60 or \$70



per barrel of crude oil.

Could Oil & Gas companies capitalise more on the “Oil” side? It is unclear... Individual companies are focusing on shorter-payback activities and expansions of already-existing projects [Eneb] & [War17c], while oil-extracting nations are cutting oil output to guarantee stable prices. Saudi Arabia is leading this cut within OPEC [Rav17a] and without OPEC (in particular, partnering with Russia [RF17]), but some countries such as Iraq, the United Arab Emirates (UAE) or Nigeria are poorly adhering to the agreement [Rav17a]. Worryingly for OPEC nations, US shale producers will go their own way regardless of OPEC production restraints [Cro17f]. As already mentioned, capitalising more on the “Oil” side is unclear...

Could Oil & Gas companies then capitalise more on the “Gas” side? It is unclear in the near term... The surge of natural gas investments has been oversupplying global markets. As a consequence, European and Asian gas markets (which account for more than 90% of LNG global demand [Ter17]) have increasingly affordable prices (down more than 40% since 2012) and increasingly flexible contracts (the fraction of LNG contracts for 10 years or more was  $\approx 95\%$  a decade ago and is  $\approx 60\%$  today) [War17a].

Despite the favourable conditions for gas buyers, the remarkable affordability of coal and the boost in renewable energy are hindering gas demand growth [War17a]. Bloomberg New Energy Finance expects that LNG demand might catch up with supply in the mid 2020’s [BNE17a] and, until then, Oil & Gas companies can address the two hindering causes with two opposite approaches: *on one hand, squeeze coal and, on the other hand, invest in green energy technologies*. Actually, these two approaches are the second and third helping hands that the bad can offer the good.

### 2.3.2 Fighting coal

Second, fighting coal makes all the environmental sense, since it is the most polluting fossil fuel. In 2015, it accounted for  $\approx 45\%$  of all CO<sub>2</sub> fuel-combustion emissions (up from  $\approx 35\%$  in 1973), even though it accounted for less than 30% of primary energy supply [IEA17b]. Fortunately for our carbon-constrained world, we are making a global shift away from coal: global coal production plummeted 6.2% in 2016, the largest annual fall on BP’s records, mainly driven by the lower coal consumption of China, the US and the UK. See how the world is gradually shifting away from coal in Figure 2.5.

Fighting coal is also making increasing financial sense, driven by the downward pressure on LNG and renewable energy prices [Cro17d] & [Tho17a], the willingness to implement carbon pricing mechanisms [XSR17] & [Kyn17] or the straightforward

phase-out of coal-fired plants in entire countries (in France in 2021/2022 or in the UK in 2025) [Buc17b] & [Cro17e].

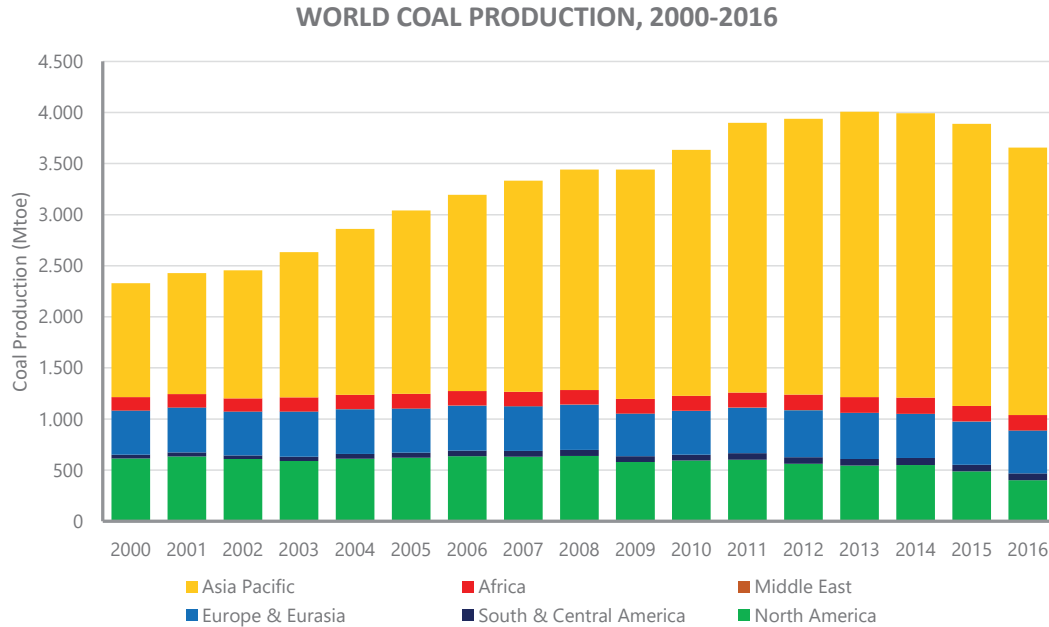


Figure 2.5: Coal production by region between 2000 and 2016, expressed in million tons of oil equivalent (Mtoe). Global coal production peaked in 2013 and decreased almost 9% between 2013 and 2016. Data from BP [BPE]

*“The fortunes of coal appear to have taken a decisive break from the past”,* in the words of Spencer Dale, BP’s chief economist [Cla17b]. These gloomy fortunes are reflected in the gloomy performance of the Stowe Global Coal Index. The Stowe Global Coal Index (“COAL”), which *“is designed to serve as a fair, impartial and transparent measure of the performance of the Global Coal Industry”* [STOa], plunged a 73% between June 2011 and September 2017.

I encourage you to compare this performance with other global financial indexes. On one hand, if you invest *only in the energy industry*, you can take a look at the MSCI ACWI Energy index (energy securities across 23 Developed Markets (DM) and 24 Emerging Markets (EM)) and the MSCI WORLD Energy Index (energy securities only across 23 DM). Those two indexes were almost unchanged in September 2017 compared to June 2011 [MSCb] & [MSCd], which is radically better than the -73% performance of “COAL”.

On the other hand, if you invest *in all sectors of the economy*, you can take a look at the MSCI ACWI (MSCI’s flagship global equity benchmark across 23 DM and 24 EM [MSCc]) and the MSCI WORLD index (broad global equity benchmark

across 23 DM [MSCe]). Between June 2011 and September 2017, the MSCI ACWI increased a 42% and the MSCI WORLD index increased a 50% [MSCa], which is definitely radically better than the -73% performance of “COAL” (Figure 2.6).

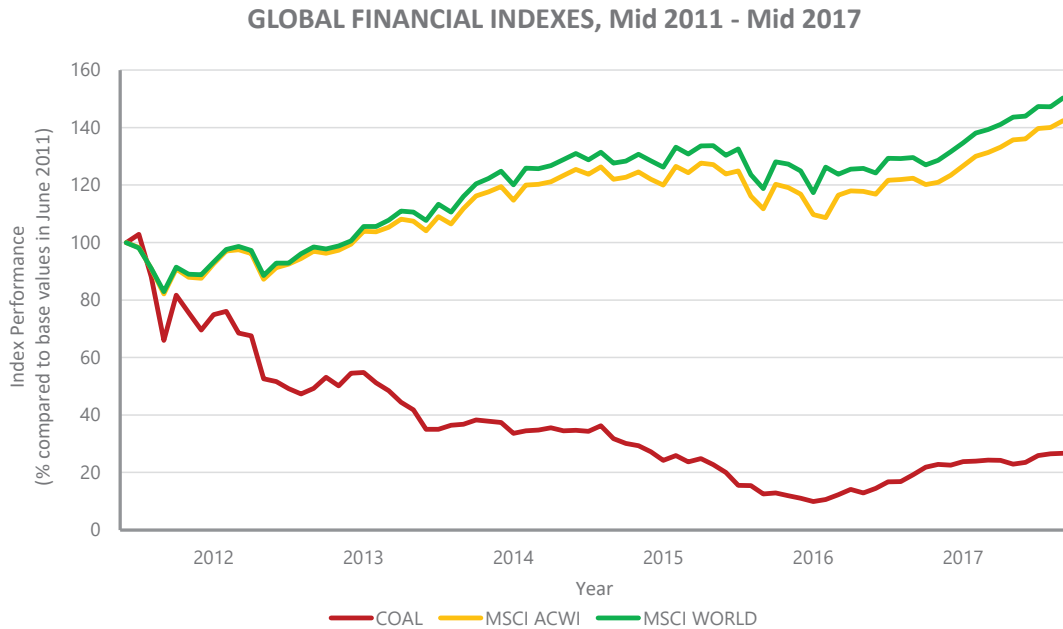


Figure 2.6: Monthly performance of global financial indexes related to the coal industry (“COAL”), a group of developed and emerging economies (“ACWI”) and a group of only developed economies (“WORLD”). The monthly values of each index for June 2011 were taken as 100% reference and the rest of values for each index are expressed as a percentage of this reference. Data from S-Network Global Indexes [Stob] and MSCI [MSCa]

It seems that your investments would have outperformed coal almost anywhere else... and individual investors and financial institutions were well aware of the underperformance of coal. The “abstract” underperformance of the Stowe Global Coal Index was accompanied by “concrete” corporate bankruptcies. Bloomberg New Energy Finance highlighted 7 coal bankruptcies in that same period [Lie17]. Take Peabody Energy, the world’s largest private sector coal miner, as an example. Peabody Energy saw how its net equity collapsed a 93% between 2012 and 2016 [Mor] and, after filing for bankruptcy, was eventually relisted on the NYSE in April 2017 [Cro17e]. Evidently, financial ratios were not and are not on the side of coal companies.

Proposed carbon pricing mechanisms will call the feasibility of coal companies further into question. The UK policy offers a model example: in 2013 the UK introduced a levy of £23 per tonne of CO<sub>2</sub> emitted (almost 5 times more than in the

rest of the European Union) [War17k] and by 2016 its coal consumption had fallen to the levels of the start of the Industrial Revolution [Cla17b]. As expected, natural gas benefited from this sharp decline [UKE17]. See the demand trends for coal and natural gas in the UK in Figure 2.7.

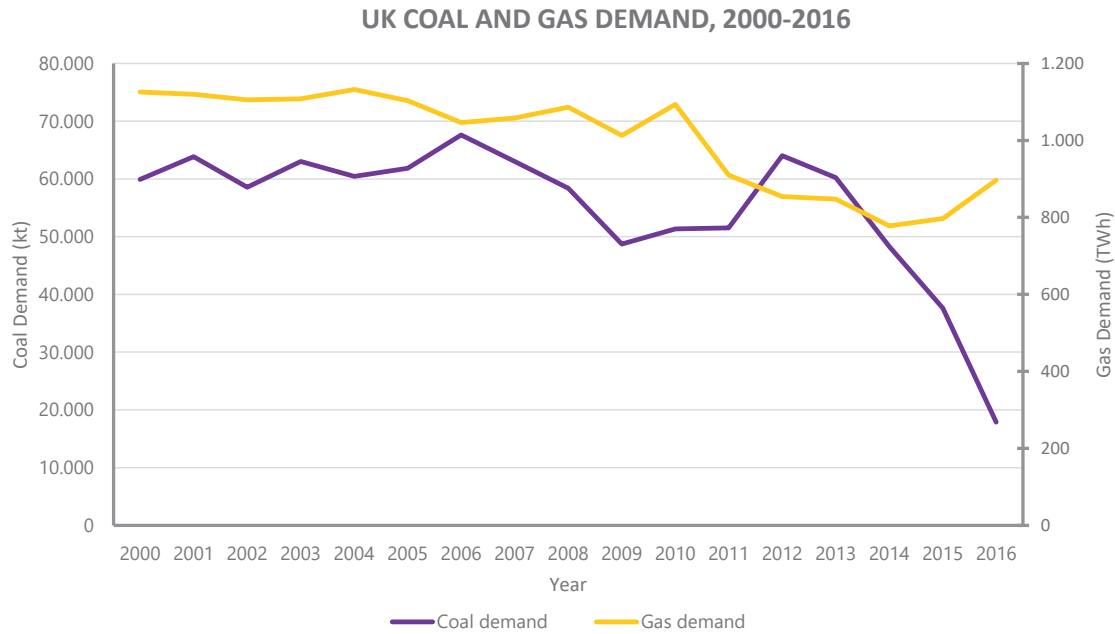


Figure 2.7: UK coal demand (left axis) between 2000 and 2016, expressed in thousand tons of coal, and UK gas demand (right axis) between 2000 and 2016, expressed in TWh. UK coal demand decreased 70% between 2013 and 2016 (compared to the 9% decrease in world coal production in that period). The sharp decline in coal was partially compensated by an increase of 6% in natural gas demand in that same period. Data from UK National Statistics in Energy Trends [fBEISUb] & [fBEISUa]

The UK’s CO<sub>2</sub> policy will remain in force at least until 2021 and, if properly extended, could ease the already-compromised phase-out of coal-fired generation by 2025 [War17k]. Lastly, place this CO<sub>2</sub> policy inside the ambitious UK’s “Clean Growth” energy strategy, that will promote offshore wind, nuclear, CCS and heat and transport energy efficiency [TW17] & [PC17]. You come to realise how exemplary is the UK’s energy transition and how under-publicised it is compared to “Brexit”.

The UK is the prime example of how the public sector can force the shift towards cleaner energy sources via carbon pricing mechanisms. The public sector should lead the push for carbon pricing, but the private sector should support it. This is where Oil & Gas companies can play a role: they need governmental regulations to drive out coal in favour of natural gas and hence they should unanimously

support the taxation of carbon emissions, which can make natural gas more affordable than coal [War17a].

We have already witnessed this corporate push by Oil & Gas companies. Remember when Ben van Beurden, Shell’s CEO, spoke about the Paris Agreement. He insisted that *“the next step should be for governments to put in place the right policies [...] These policies should include government-led carbon pricing mechanisms”* [vB17]. Remember when the Climate Leadership Council proposed redistributive carbon taxes in the US. 4 Oil & Gas supermajors (namely BP, ExxonMobil, Shell and Total) backed the proposal from the beginning, as you can see in Figure 2.8.

Further corporations are fostering the shift away from coal, even without the help of carbon pricing mechanisms. A couple of examples are American Electric Power in the US and AGL Energy in Australia. American Electric Power, the largest electricity generator from coal in the US in 2015, has been reorienting towards renewable energy and in July 2017 announced a \$4.5 billion investment to build the largest wind farm in the US [Cro17e]. AGL Energy, the largest utility in Australia, is aiming at a future without coal [Smy16c] and in 2016 set out plans for phasing their first coal-fired plants in 2022 [Smy17a].

All this corporate push should gain momentum worldwide. Those who can lobby, such as big Oil & Gas companies, should lobby governments to introduce extensive carbon pricing mechanisms (maybe taking as starting points the national scheme of the UK or the regional pilot schemes of China). Those who cannot lobby so much, such as utilities, should shift away from coal towards natural gas or renewable energies. It seems “clear” from the private, corporate perspective.

# THE CONSENSUS CLIMATE SOLUTION

**The Founding Members of the Climate Leadership Council believe that America needs a consensus climate solution that bridges partisan divides, strengthens our economy and protects our shared environment.**

The Council's carbon dividends solution embodies the conservative principles of free markets and limited government. It also offers an equitable, popular and politically-viable way forward, paving the way for a much-needed bipartisan climate breakthrough.

Our carbon dividends program is based on four interdependent pillars:

1. A gradually rising and revenue-neutral carbon tax;
2. Carbon dividend payments to all Americans, funded by 100% of the revenue;
3. The rollback of carbon regulations that are no longer necessary; and
4. Border carbon adjustments to level the playing field and promote American competitiveness.

This plan would achieve significantly greater emissions reductions than all current and prior climate regulations, while helping America's businesses and workers get ahead. In fact, the bottom 70% of Americans would be financially better off.

**Our carbon dividends solution is: Pro-Environment, Pro-Growth, Pro-Jobs, Pro-Competitiveness, Pro-Business and Pro-National Security.**

Working with a range of constituencies, the Climate Leadership Council will develop and promote a consensus climate solution based on these pillars.

## Corporate Founding Members



**ExxonMobil**



*Johnson & Johnson*

**P&G**



**PEPSICO**



**Schneider  
Electric**



**TOTAL**



## NGO Founding Members

CONSERVATION  
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Paid for by the Climate Leadership Council

Figure 2.8: 4 Oil & Gas supermajors (BP, ExxonMobil, Shell and Total) backed the redistributive carbon taxes proposed by the Climate Leadership Council

Unfortunately, governments have blown hot and cold about coal and carbon taxes. Besides the exemplary carbon tax in the UK or the coming carbon tax in China (which is also emerging as the unequivocal leader in adding renewable energy generation [Cro17g]), the examples of the US, Australia, Germany or India are darkening our climate future with their black fumes of coal. These last anti-heroes are above all protecting their domestic natural resources, awash with coal, since they hold some of the largest coal reserves in the world (Figure 2.9). These resources translate ultimately into national energy security, national jobs and, of course, favourable votes.

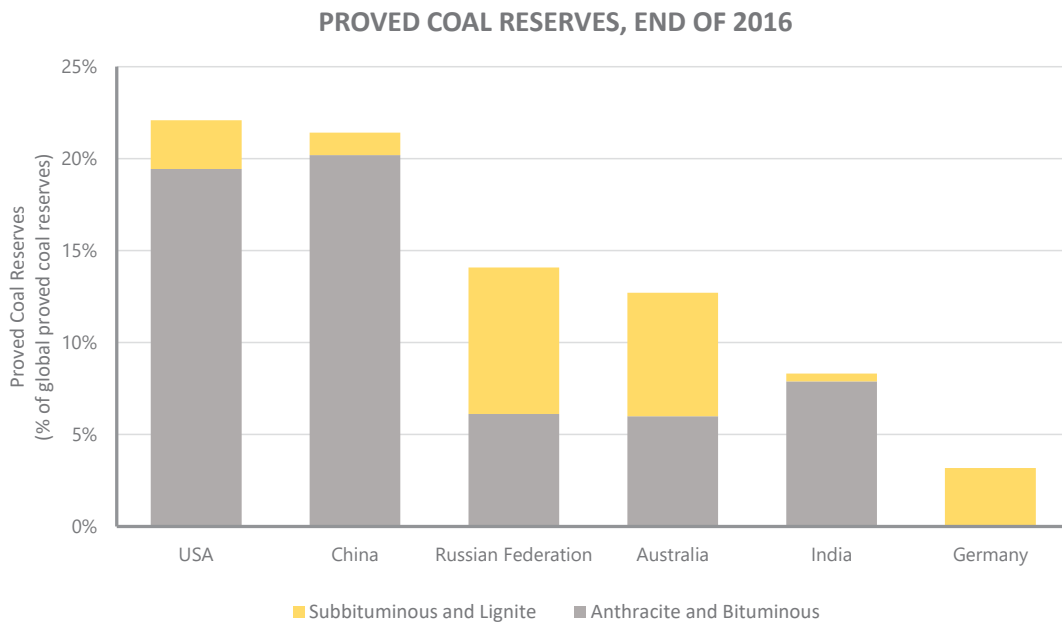


Figure 2.9: National proved reserves of coal at the end of 2016, as a percentage of world proved reserves of coal at the end of 2016. Six countries concentrate the 82% of world proved reserves of coal and, unsurprisingly, at least four of them have pro-coal governments. Data from BP [BPS17]

As for the **US**, the strategy of American Electric Power is aligned with many other US utilities: an average of 8.5 GW of coal generation capacity was retired every year between 2012 and 2016 and currently there are no new coal plants under construction in the US [Cro17e]. However, this corporate vision opposes the vision of US president Donald Trump. “*Trump digs coal*” during the electoral campaign and, in the same spirit, “*Trump withdraws Paris*” [Agreement] during the first months of its administration [SJC17a]. As a matter of *curiosity*, the US holds the largest coal reserves in the world and has enjoyed the lowest coal prices worldwide since 2009 [BPS17]...

However, even with presidential support, coal in the US will undergo hard times as the US shale revolution continues to unfold. In the words of Bob Dudley,

BP’s CEO: “*You only have to look at the situation in the US where GHG emissions are back down to where they were in the 1990’s. As you well know, that’s largely because the shale revolution has produced abundant, cheaper gas, which has been displacing coal in the American energy mix*” [Dud17]. As a more concrete example, almost 2/3 of electric capacity additions under construction in the US are natural gas plants [CK17b].

As for **Australia**, the strategy of AGL Energy opposes the vision of the Australian government, who in 2014 became the first country to repeal a carbon tax and has recently announced a new energy plan without subsidies for renewables and without taxes for carbon [Smy16a]. As a matter of *curiosity*, Australia holds the fourth-largest coal reserves in the world [BPS17] and is the world largest coal exporter [Smy16a]...

A further example is **Germany**, who is planning to phase out all nuclear electricity generation by 2022 and, most likely, the gap will be replaced by coal. Most recently, at the COP23 hosted by Germany in November 2017, Germany itself was notably absent from an international pledge to phase out coal-fired generation by 2030 [Buc17a]. As a matter of *curiosity*, the share of domestic coal production in Germany has been decreasing for decades [IEAc], even though Germany holds the third-largest reserves of low-graded coal (subbituminous and lignite) in the world [BPS17]...

The last national example that we will mention is **India**, where coal dominates the new capacity additions well above wind and solar in the current five-year governmental plan. Recently, Piyush Goyal, the Minister of Railways & Minister of Coal in India, reminded the Indian parliament that coal “*will remain and continue to remain our mainstay and there was no such agreement in Paris that will stop us from continuing to encourage coal-based generation of power*” [Spo17b]. Resorting to the most affordable coal seems reasonable for a lower-middle-income economy like India, where only 7 out of 10 households have access to electricity [Sin17]. However, as a matter of *curiosity*, India holds the fifth-largest coal reserves in the world [BPS17]...

Despite these national antiheroes, coal is losing the battle on the global stage. The world is shifting away from coal, where its global production plummeted 6.2% in 2016, and could further plummet if governments implemented more stringent carbon pricing mechanisms. This is precisely the second area where Oil & Gas companies can help the good: by fighting coal, by promoting and lobbying for more stringent carbon pricing schemes. Notwithstanding, the collaboration of Oil & Gas companies with the good does not stop here: there is eventually a third area where they can help and is by investing in the good, by diversifying into green energy technologies.



### 2.3.3 Diversifying into green technologies

*Advanced energy acceleration could drive a convergence in the energy system. More companies that today identify as “oil and gas companies” or “power developers” or “technology manufacturers” may increasingly integrate business models as “energy companies”. Multiple forces underlie this convergence [...] Electrification of transport and heating would create a bridge between the oil and gas and electric power sectors [...] Oil and gas companies have the capital and longer time horizons, and are looking for opportunities to diversify in the face of uncertainty over liquids demand for transport and over broader climate policy.*

*World Economic Forum, McKinsey & Company*

*“Game Changers in the Energy System - Emerging Themes Reshaping the Energy Landscape”, [WEF17a]*

Third, diversifying into green energy technologies makes all the environmental sense, since they are cleaning the consumption points (such as with extended electrification) as well as cleaning the generation points (such as with renewables or nuclear, whose lifecycle CO<sub>2</sub> emissions per MWh are typically one or two orders of magnitudes lower than the values for oil, coal and natural gas [TBA13]).

Diversifying into green energy technologies also makes all the financial sense, because renewables are increasingly affordable and are best positioned to lead the energy transition *in the long run* [War17a]. This last point must be at the core of all forward-looking strategies for Oil & Gas companies: if they want to maintain their share of the energy industry, sooner or later they will have to become “beyond-fossil energy companies”.

Shell best illustrates the spirit of green-energy diversification among Oil & Gas giants [War17i]. In the words of Ben van Beurden, Shell’s CEO: *“We aim to grow our offer of low carbon energy [...] What does this mean in concrete terms, you might ask. Well, for example, we aim to grow investment in our recently established New Energies business to perhaps \$1 billion a year by the end of the decade [...] To be clear: Shell is already involved in new energies — like our wind parks here in the US. But I expect new energies to grow as part of our portfolio over time”* [vB17].

Shell is in fact following words with deeds and most recently bought one of Europe’s largest EV charging companies [SC17] and decided to sell electricity directly to industrial customers in the UK and most probably also in the US [But17g]. They are modestly gambling (\$1 billion a year, compared to \$25-\$30 billion of total yearly investments) on a range of technologies, so that mistakes are not too big and so that successes lead to higher investments [War17i].

Shell is the most visible exponent of an industry-wide strategy. 7 Oil & Gas companies invested altogether nearly \$15 billion in renewables between 2012 and

2016 [Cla17a] and 10 Oil & Gas companies committed to invest altogether \$10 billion between 2017 and 2026 to help fight climate change, initially focusing on CCS systems [Cla16].

As you see, more and more companies apart from Shell are stepping “outside their comfort zones”. A close example to Shell is Total, who has recently invested \$2.5 billion in battery and solar companies [War17i], bought a 23% stake in Eren Renewable Energy [Keo17b] and bought a European clean-fuel-charging company [SC17]. A not-so-close example to Shell is Saudi Aramco, owned by Saudi Arabia, because the diversification of Saudi Aramco will go beyond the corporate boundaries. The underlying reason is this: the sell of a (minority) stake in Saudi Aramco will finance the (wider) economic reform of Saudi Arabia beyond oil [Cro17h]. *“We are determined to reinforce and diversify the capabilities of our economy, turning our key strengths into enabling tools for a fully diversified future. As such, we will transform Aramco from an oil producing company into a global industrial conglomerate”*, in the words of Mohammed bin Salman, Crown Prince of Saudi Arabia [Vis].

Saudi Aramco is the largest state-owned Oil & Gas company. There are many more, such as CNPC in China, PDVSA in Venezuela or NNPC in Nigeria, which in some cases are the *only* financial backbone of their owning states. Unfortunately for them, the downturn in oil prices decreased the revenues of OPEC states by more than 60% between 2012 and 2016 (in absolute terms, \$750 billion less in 2016 than in 2012, adjusting to real 2016 dollars). See for yourself the long-term diminishing trend of OPEC oil rents in Figure 2.10.

This is why Nick Butler declares that *“the structural fall in the oil price is the most destabilising economic event to have hit the world since the financial crash of 2008”*. At least five OPEC states are threatened by severe political and financial destabilisation (including Venezuela and Nigeria), civil unrest is already visible in Libya and latent in Algeria [But17f].

What will happen in Saudi Arabia? Nobody knows. The global shift away from oil underlies the national reform strategy, “Vision 2030”, and Saudi Aramco’s IPO plays a key role in that strategy. However, the initial intended valuation for Saudi Aramco at \$2 trillion seems too optimistic (approximately the double of Financial Times’ estimation [CR17]) and clashes with its traditional governance (must shed the opacity of company assets, must protect the interest of minority stakeholders [But17i]). There are voices that favour a private share sale to foreign governments and institutions [RFKM17], there are voices that say that China is the most likely buyer in that private sale [But17c].

Nobody knows what will happen. However, in the middle of this uncertainty, we are sure of two things: Oil & Gas companies are diversifying to become “beyond-fossil energy companies” and they need time for this diversification.

## OPEC OIL RENTS, 2005-2015

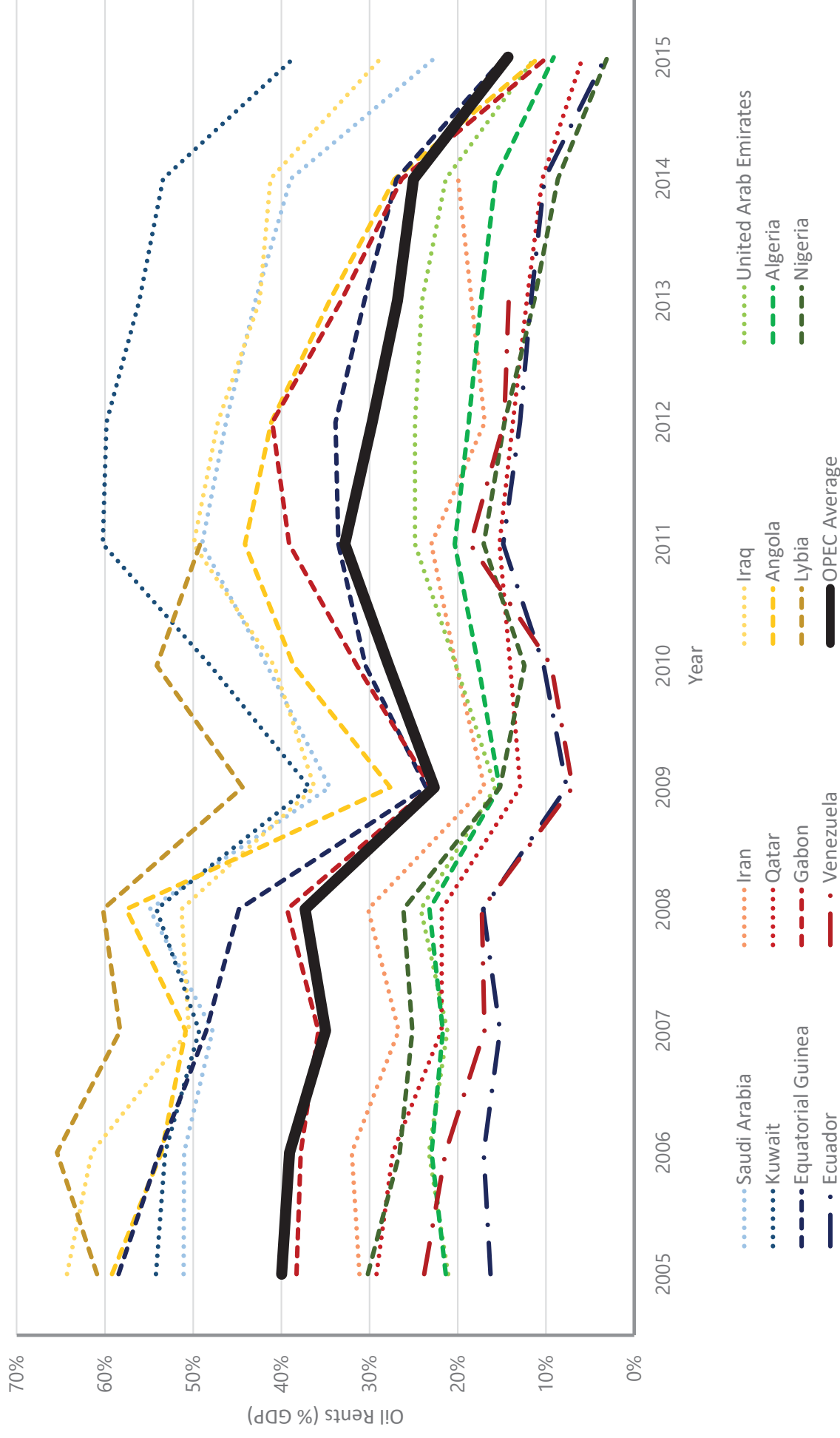


Figure 2.10: OPEC oil rents as a % of national GDP between 2005 and 2015. As defined by The World Bank: “Oil rents are the difference between the value of crude oil production at world prices and total costs of production”. Middle-East countries are dotted lines, African countries are dashed lines and American countries are dash-dot lines. Average OPEC oil rent is computed for each year and is represented as a solid line. Average OPEC oil rents have declined from values of  $\approx 40\%$  of national GDP in 2005 to values  $\approx 15\%$  of national GDP. Data from The World Bank [WBO]

In a nutshell, the bad are internally divided and **Oil & Gas companies could become unexpected allies of the good**. Looking into the shorter term, Oil & Gas companies are *shifting from oil towards natural gas*, investing so heavily in LNG that its supply is on course to increase by 50% between 2014 and 2021. Meanwhile, lower fossil fuel prices and shorter-term contracts have endangered the commercial viability of this LNG surge. As a consequence, Oil & Gas companies have immediately responded by *fighting coal* to make place for their gas, for example lobbying for carbon pricing mechanisms. Looking into the longer term, Oil & Gas companies will become “beyond-fossil energy companies”, *diversifying into green technologies*.

The bad are internally divided and Oil & Gas companies could, “sooner or later”, become unexpected allies of the good. The only problem here is that the “sooner or later” just mentioned has more to do with “later” than with “sooner”. **Oil & Gas giants, either state-owned or publicly-owned, need time to diversify**. The instability inside the OPEC countries serves as warning: if an energy transition away from fossil fuels unfolds too fast, these countries will lose their financial backbones and their geopolitical influence in the blink of an eye. The same applies at the corporate level: they are betting small on green technologies while investing big in oil and bigger in natural gas, which are still fossil fuels.

Even Shell, the “green leader”, prefers moving too slowly over prematurely investing in technologies that they do not understand [War17j]. Ben van Beurden, Shell’s CEO, has emphasised that time and again: “*The point that you can be too early was proved by us [...] We were among the first of the big international Oil companies to get into solar and we found out we could not make any money out of it*” [War17j]. “*I don’t want us to get ahead of ourselves [...] I am sure we will make mistakes, but I don’t want them to be big mistakes*” [War17i]. “*All the milestones, we are either ahead or on track [...] But you are never done in this industry because everything is always in continuous decline*” [War17j].

The bad need time to diversify and the energy transition cannot afford to give away more time: *we know the direction, the problem now is the urgency*. The good will surely appreciate this help of the bad, but that will not be enough.

Saruman: “*You did not seriously think that a hobbit could contend with the will of Sauron? There are none who can. Against the power of Mordor there can be no victory. We must join with him, Gandalf. We must join with Sauron. It would be wise, my friend.*”

Gandalf: “*Tell me, friend, when did Saruman the wise abandon reason for madness?*”

*J.R.R Tolkien*

*“The Lord of the Rings: The Fellowship of the Ring”, film adaption*

## 2.4 Could the *ugly* reach out to the good?

The answer is unsurprisingly “yes”, because the ugly are an untapped potential of green technologies. In fact, the ugly *ideally* account for the largest reduction in CO<sub>2</sub> emissions between the RTS scenario (emissions under the current NDCs of the Paris Agreement) and the 2DS scenario (2.0°C increase by 2100 with 50% probability, designed via multidisciplinary optimisation [Enea]). All renewables account for 1/3 of the ideal reduction in CO<sub>2</sub> emissions between these two scenarios, while all remaining green technologies account for 2/3 [IEA17d]. We obtain similar conclusions comparing the “New Policies Scenario” and the “66% 2.0°C Scenario” [IEA17c].

However, as you may remember, even some renewables are not currently among the good, because some renewables are currently underestimated or underinvested. Take the example of hydropower, which generates worldwide twice as much clean electricity than non-hydro renewables [IEA17b], but it is not making as many headlines. Actually, hydropower resembles the ugly in the sense that it is *forgotten*. This is the common trace of the ugly: they are *forgotten solutions*. Who are we forgetting? To introduce them, we will borrow a quote from the US writer Kurt Vonnegut Jr.: “*There are too many of us and we are all too far apart*”.

On one side, the ugly are “*too many*”. In 2016, IEA analysed the deployment of 26 technologies for the energy transition and only 3 out of 26 were “on track” to meet the 2DS targets for 2025 [IEA17d]. If you take a *first* closer look at the 26 technologies, you notice that 4 of them are double-counted, because they are aggregate categories (“Transport”) embracing a series of smaller, already-counted subcategories (“Electric Vehicles”). That leaves us with 22 independent technologies. If you take a *second* closer look at the 22 independent technologies, you notice that 3 of them are *clearly* the good (“Solar PV and onshore wind”, “Electric Vehicles” and “Energy Storage”) and 3 are *clearly* the bad (“Natural gas-fired power”, “Coal-fired power” and “Fuel economy of light-duty vehicles”). That leaves us with 16 forgotten technologies, 16 partial solutions. These are the “*too many*” ugly.

On the other side, the ugly are “*all too far apart*”, in the sense that they are very different from each other. Some of them are forgotten sources of renewable energy, such as bioenergy or hydropower. Some of them are deployed in the transport sector, some in the industrial sector, some in the buildings sector. How could CCS, international shipping, cement production and building envelopes fit into the same box? They do fit into one: the ugly, even though they are “*all too far apart*”. (Even the same energy vector can participate in various independent technologies: for example hydrogen can play different roles in 2 industrial technologies, 3 transportation technologies and gas-fired electricity generation [IEA17d]).

Hopefully we had time to analyse all these forgotten technologies, that are

*“too many and all too far apart”*. Unhappily, they are indeed *“too many”*, 16 partial solutions, to treat them all in this master thesis. You could rightly see the glass half-empty, since we are leaving some forgotten solutions still in oblivion. Nonetheless, you could rightly see the glass half-full, since the ugly as a whole now have a face and may make more headlines in the coming years.

In essence, an ideal solution for the energy transition is **1/3 renewables, 2/3 other green technologies**. The ugly are many (16 independent technologies, even some renewables) and diverse. We will introduce 3 of them. The first of them is no independent technology; instead, it is an overarching group of them: “energy efficiency”. The second and third of them are indeed independent technologies, two “eternal promises”: “Carbon Capture and Storage” and “Nuclear Energy”. The rest of forgotten technologies should not remain forgotten for long and future research should analyse their real potential, taking [IEA17d] as reference (see Figure 2.11).



Figure 2.11: IEA selection of the 26 technologies involved in our sustainable energy transition. The colours represent deployment compared to the 2DS targets for 2025: green (on track), orange (improvement, but more efforts needed) and red (not on track). The arrows represent the recent development trend. Credit: IEA [IEA17d]

### 2.4.1 Energy efficiency

Most of the ugly fall into the category of energy efficiency, which is ultimately related to *energy intensity*: the amount of primary energy needed to produce one unit of GDP. Global energy intensity has been decreasing for decades (an average yearly decrease of 1.3% between 1970 and 2010) and lately faster than before (an average yearly decrease of 2.1% between 2010 and 2016) [IEA17a]. This progress points to an “energy-economy decoupling”: between 1990 and 2014, GDP grew by more than 90% while primary energy supply grew by only 56%. Some countries are outstanding examples, such as China, where energy intensity decreased by 62% [IEA16d].

We can segment the global energy intensity by income-classified country categories (Figure 2.12). All categories are improving their energy efficiency, especially the lower-middle-income, whose average energy intensity decreased a 43% during the period. Low-income countries still have huge potential for energy savings, since their energy intensity in 2014 was twice as large as for lower-middle-income countries [WBEb]. This is why we emphasised that *all* countries must focus on efficiency, even developing economies, since typically these economies have more energy-intensive industries and use less efficient energy technologies in all their economic sectors.

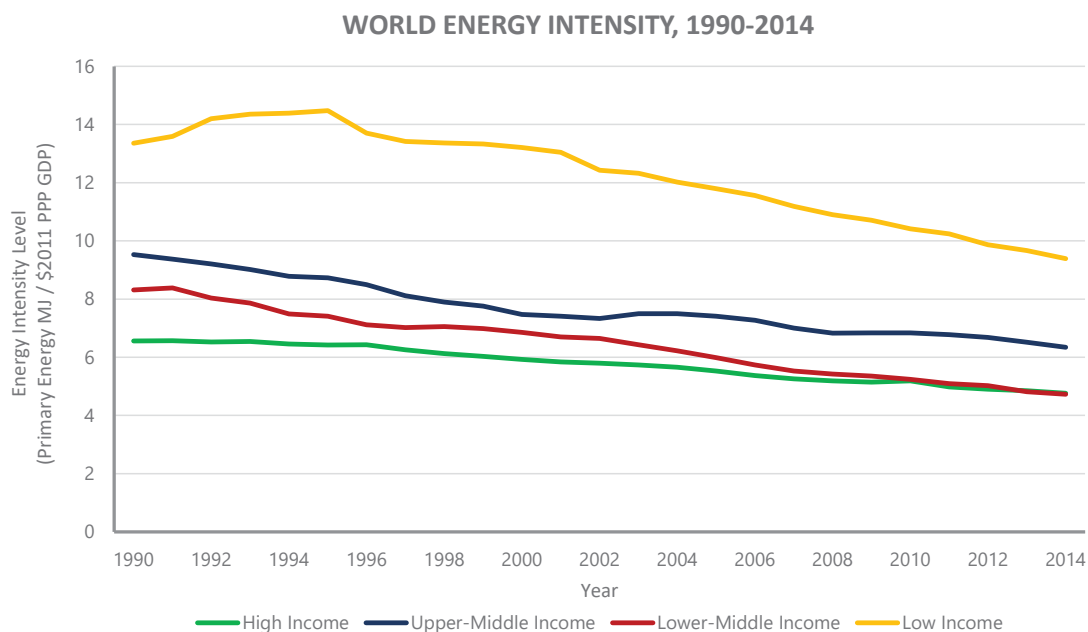


Figure 2.12: Energy intensity for the 4 income-classified country categories between 1990 and 2014, expressed in MJ of primary energy supply divided by GDP (adjusted for \$2011 and Purchasing Power Parity (PPP)). The country classification refers to 2015 GNI per capita (although in reality a country could have belonged to different income categories during the period). Data from The World Bank [WBEb]

If you put all efficiency improvements in perspective, the cumulative energy savings are staggering. The world would have used 12% more primary energy in 2016 if we had missed all energy efficiency improvements since 2000 and that is comparable to adding another European Union to the global energy market [IEA17a].

Falling energy intensity has been the main driver flattening energy-related GHG emissions since 2014 [IEA17a] and should further reduce them in the future. The contributions of energy efficiency in the IEA scenarios are definitely substantial: they should account for 33% of overall CO<sub>2</sub> reductions (comparing the “New Policies Scenario” and the “66% 2.0°C Scenario” [IEA17c]) or even 40% of overall CO<sub>2</sub> reductions (comparing the “RTS” and the “2DS” scenarios [IEA17d]). Besides, energy efficiency lies at the foundation of energy security: the need for less energy in the first place is better than any diversified, clean energy sources [Boc17].

Despite progress hitherto, 2/3 of world energy use are not regulated by efficiency standards. The coverage is geographically uneven, led by China, and sectorally uneven, fostered by the industrial and residential sectors and stalled by freight transport. Take the example of trucks: only 1/6 of its worldwide energy use was covered in 2016 (still only 4 countries regulate their energy efficiency), even though they represented 43% of global oil consumption for road transport. Even the leading sectors, such as the residential sector, suffer from geographical-sectoral unevenness. Take the example of space-cooling demand, which is rising fastest in countries with the least stringent efficiency regulations for air conditioning [IEA17a].

How could governments foster progress in energy efficiency?

On one hand, governments can impose minimum energy performance levels for appliances to enter the market, such as with vehicles, household appliances or industrial equipment. As an example, the European Union, India, South Korea and Mexico are planning to regulate soon the fuel economy in trucks. In parallel, the “Internet of Things” is facilitating energy savings as more “connected devices” are connected in households: 4 billion at the end of 2016 and another 1 billion expected to come online in 2017, even reaching the 3 billion yearly additions by 2020 [IEA17a].

On the other hand, governments can impose efficiency targets for individual firms or entire economic sectors, such as with tradeable “white certificates” (energy saving obligations). As an example, France and Italy (the two biggest trading markets of white certificates) reinforced in 2016 their policies to substantially increase the market value of energy savings [IEA17a].

Taking the public sector as a whole, one way to assess the overall policy progress is the Efficiency Policy Progress Index (EPPI), which analyses changes in the coverage and strength of mandatory energy efficiency policies. Taking the EPPI as reference, the overall policy progress in 2016 was the slowest since 2010,



as you can see in Figure 2.13. Almost all the coverage progress in 2016 came from continuing impact of earlier policies, while only a fraction came from new policies (only two significant policy additions, namely air conditioning standards in Indonesia and refrigerator and freezer standards in China). Beyond coverage, the strength of mandatory efficiency policies grew at the lowest rate in recent years [IEA17a]. As you can see, public policy is losing momentum.

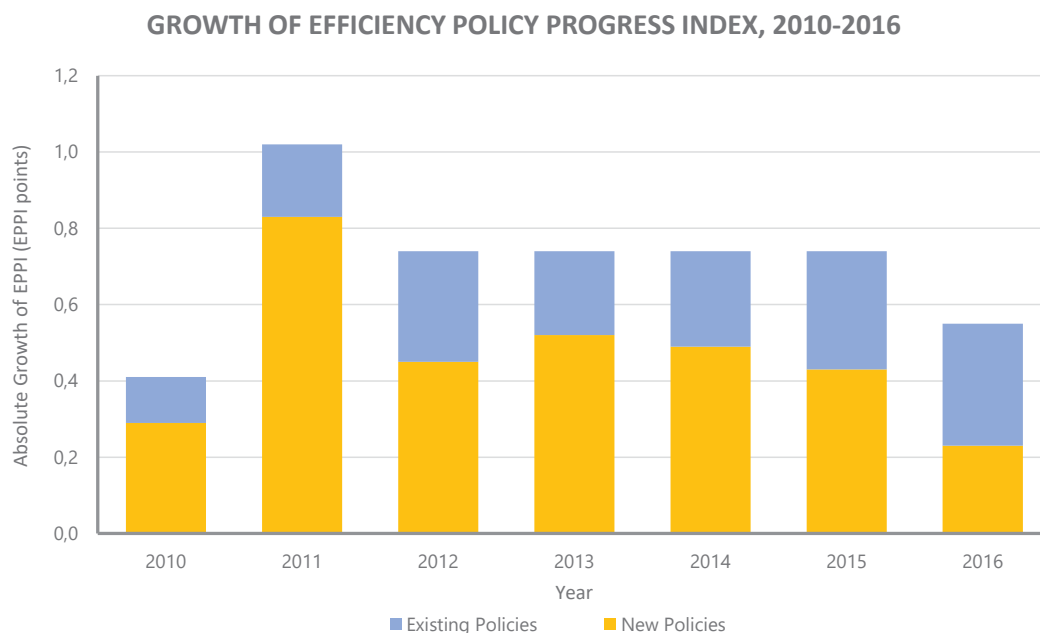


Figure 2.13: Annual growth of the Efficiency Policy Progress Index (EPPI) between 2010 and 2016, expressed in change in EPPI points. We segment between the impact of existing policies and new policies. The contribution of the latter in 2016 was the lowest since 2010. Data from IEA [IEA17a]

Fortunately, the private sector can also foster the extended deployment of energy efficiency. On one hand, BlackRock found a surprising correlation between financial performance and energy efficiency improvement: companies in the MSCI WORLD Index that improved the most their carbon efficiency (annual CO<sub>2</sub> divided by annual sales) were also the ones that performed better relative to the MSCI WORLD Index [Bla16]. Whatever the causation is that underlies this correlation, it is good news for the companies in particular and for energy efficiency in general.

On the other hand, the global market for energy service companies (providing energy-efficiency services to the final energy users) grew by 12% to \$27 billion in 2016, employing over 1 million people around the world [IEA17a]. Nonetheless, compare these numbers with those of ConocoPhillips in 2016, the by-far smallest “Oil supermajor”, with \$24 billion in revenue and only 13300 employees [Cona].

As you can see, there are no such things as “Efficiency supermajors”: compared to the big Oil & Gas companies, energy service companies share a minor, more fragmented and more diverse market. Consequently, they scarcely have lobbying influence over public policies. This is the takeaway: private sector is apparently pulling in the same direction, but the initiative lies with the public sector and, unfortunately, the public sector is poorly delivering lately.

In short, energy efficiency (“reduced energy intensity”) embraces most of the ugly. Global energy intensity has been decreasing for decades, has been the main driver flattening energy-related GHG emissions since 2014 and should ideally be the main driver reducing them in the near future. Despite progress hitherto, 2/3 of world energy use are not regulated by efficiency standards. The coverage is geographically uneven, led by China, and sectorally uneven, fostered by the industrial and residential sectors and stalled by freight transport. The public and the private sector are united, but the public sector initiative is lagging behind.

## 2.4.2 Carbon Capture and Storage (CCS)

Beyond energy efficiency measures, CCS is the only technology that can *theoretically* -and very significantly- curb emissions from the continued use of fossil fuels in electricity generation and in industrial processes [IEA16a]. In this sense, IEA assumes that CCS could account for 10% of overall CO<sub>2</sub> reductions (comparing the “New Policies Scenario” and the “66% 2.0°C Scenario” [IEA17c]) or even 14% of overall CO<sub>2</sub> reductions (comparing the “RTS” and the “2DS” scenarios [IEA17d]). The promises are all the more ambitious, since CCS could theoretically play a more crucial role in delivering *negative* CO<sub>2</sub> emissions in the future [IEA16a].

Existing CCS projects include a couple of CCS coal-fired plants in Canada and the US, an iron and steel manufacturing plant in the United Arab Emirates and further processing plants in 6 countries (destined to natural gas, hydrogen, fertiliser or coal gasification processing). The largest CCS projects already online are two natural gas processing plants in the US: Century Plant, operating since 2010 and with a storage capacity of 8.4 “mtpa” (million tonnes of CO<sub>2</sub> per year) and Shute Creek Gas Processing Facility, operating since 1986 and with a storage capacity of 7.0 mtpa. The largest CCS project under construction is expected to come online in 2018 at the Gorgon LNG plant in Australia, also related to natural gas processing, with a storage capacity between 3.4 and 4 mtpa [IEA16a] & [Che] & [CCSa].

The CCS deployment in particular in electricity generation is crucial in the 2DS scenario, where it accounts for 56% of all CO<sub>2</sub> *captured*. More specifically, CCS in coal-fired plants should account for 45% of all CO<sub>2</sub> captured. In a “no CCS in power” alternative of the 2DS scenario, virtually all coal-fired electricity generation

should be eliminated and the renewable technologies expanded by an additional 1900 GW above the original 2DS requirements [IEA16a].

Designing future CCS coal-fired plants and retrofitting CCS on existing ones become thus of paramount importance. Take the example of China, where 310 GW of existing coal-fired generation already meets the *theoretical* criteria for suitability for CCS retrofitting [IEA16e]. Now the obvious question is: “Is CCS fulfilling these high expectations?”

In spite of this promising potential, the *real* numbers for CCS are lagging far behind. If we account for *all* CCS projects online as of October 2017 [CCSa], they can capture less than 0.1 % of global CO<sub>2</sub> emissions [JRC16], which is comparable with capturing all yearly CO<sub>2</sub> emissions of Cuba [WBC].

Looking into the future, if all large-scale CCS projects in the pipeline (under construction, in advanced development or in early development) finally materialised, global CCS capacity in the 2020’s would double current capacity (Figure 2.14). As a consequence, it could capture all yearly CO<sub>2</sub> emissions of Cuba *and* New Zealand [WBC]. The IEA acknowledges this clash with reality in a very polite way: “*CCS is moving forward, albeit slowly*” [IEA16a].

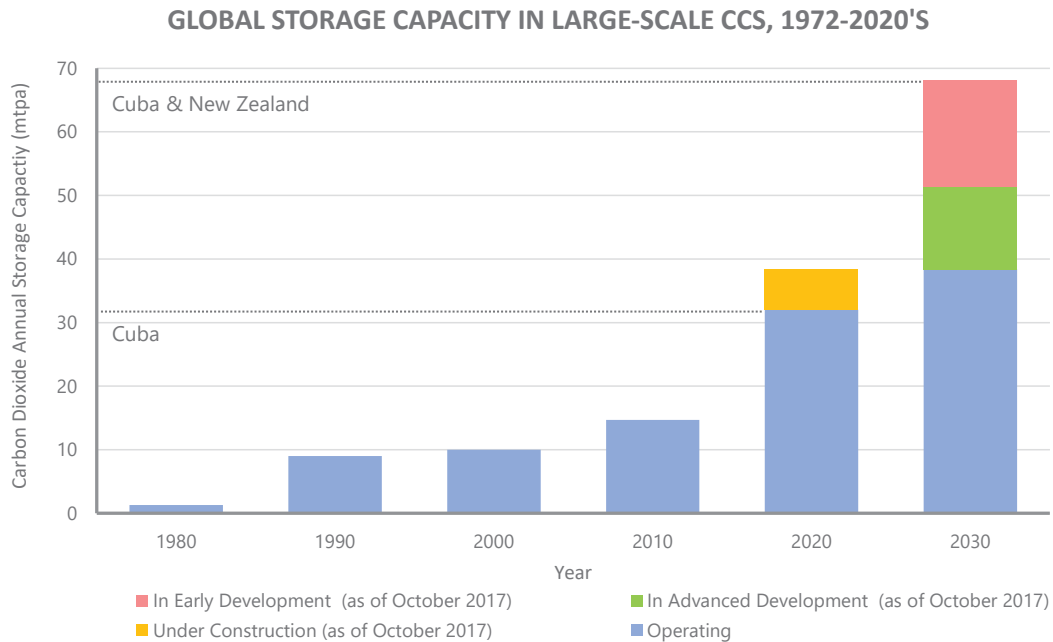


Figure 2.14: Global storage capacity in large-scale CCS projects between 1972 and the 2020’s, expressed in mtpa available at the *start* of each decade. If one project had different estimates for its mtpa value, we always took the most optimistic estimate. Data from IEA [IEA16a] and the Global CCS Institute [CCSa]

Only 17 large-scale CCS projects are operative worldwide as of October 2017 [CCSa]. What makes matters worse is that Enhanced Oil Recovery (EOR) projects are over-represented (13 out of 17 enhance fossil fuel production) and that power generation is under-represented (only 2 out of 17 capture CO<sub>2</sub> from coal-fired plants).

On one hand, EOR projects are over-represented: 13 of the 17 CCS operational projects use their captured CO<sub>2</sub> to enhance crude oil production. Even more EOR projects are in the worldwide CCS pipeline: 3 out of 4 in construction, 3 out of 5 in advanced development and 3 out of 11 in early development [CCSa]. For example, Asia’s first commercial CCS project (Yanchang Integrated CCS Demonstration) will capture CO<sub>2</sub> from the chemical industry and employ it for EOR in oil fields in the Ordos Basin in central China [Fen17] & [CCSb]. Isn’t it paradoxical to alleviate climate change by enhancing fossil fuel production? [Cro17k]

On the other hand, CCS in electricity generation is under-represented: only 2 successes (Boundary Dam and Petra Nova) and 1 failure (Kemper County). Petra Nova and Kemper County are the opposite stories of proven and new technologies. Both were expected to come online in early 2017 in the US. Petra Nova had been designed as an “established” coal-fired unit with an “established” CCS technology (a process from Mitsubishi Heavy Industries in use since 1999), whereas Kemper County had been designed as an “innovative” Integrated Gasification Combined Cycle. In the end, Petra Nova came online on time and in budget, whereas Kemper County was \$4 billion over budget and had to switch from coal to natural gas since its innovative CCS technology never worked as designed [Cro17k] & [Fou17].

No further large-scale CCS projects for electricity generation are under construction or in advanced development. Fortunately, 7 large-scale CCS projects (4 of them in China) for electricity generation are in early development for the 2020’s [CCSa]. If all these 7 large-scale CCS projects finally materialised, they could capture the equivalent of all yearly CO<sub>2</sub> emissions from Tanzania [WBC].

In a nutshell, CCS should play an essential role if fossil fuels do not significantly disappear from electricity generation and industrial processes, but **CCS is very visibly coming short of expectations**. Its deployment is and will likely be negligible (global CCS capacity in the 2020’s may only capture all yearly CO<sub>2</sub> emissions of Cuba and New Zealand) and, funnily enough, CCS is mostly dedicated to enhancing fossil fuel production.

CCS capacity should expand tenfold to meet the 2DS targets for 2025 [IEA17d] and neither the private sector nor the public sector are closing the gap. The failure in Kemper County is the most visible symptom of the decreasing R&D public investment in CCS over the last few years in IEA member countries. This trend should be immediately reversed and two investment priorities should be in-plant technology and the mapping of geological CO<sub>2</sub> storage sites [IEA17d].

### 2.4.3 Nuclear energy

Nuclear fission energy, this “nonrenewable but equally clean source of energy”, is probably the most controversial of all the ugly. I first came upon this controversy in the online course “*Energy Within Environmental Constraints*”, offered by HarvardX and directed by David Keith. When David reached the “Nuclear Energy” chapter, he warned us: “*Nobody knows if nuclear will be important or unimportant to 21<sup>st</sup> century energy [...] There are wildly different views and often different facts on topics such as radiation risk, waste, accidents - and so we will make sure that you get a range of viewpoints on some cross-cutting topics like these*” [DK].

The future of nuclear energy (nuclear fission, unless otherwise specified) is indeed uncertain, even though nuclear energy currently generates 1/3 of all low-carbon electricity [IEA17d] and should account for 5-6% of overall CO<sub>2</sub> reductions in IEA scenarios [IEA17c] & [IEA17d]. Truth to be told, discouraging events for nuclear energy are converging, both on the private and public sector sides.

On the private sector side, both operating and under-construction reactors are under threat. As for the operating reactors, more than half of the 448 operating nuclear reactors are over 30 years old and, therefore, are scheduled to be retired in the coming years [IAE17a]. But age is not the only threat to existing nuclear reactors: economics is also a threat, *either if you stay open or shut down*.

On one hand, it is a challenge to go on *operating*. Take the case of the US (1<sup>st</sup> largest nuclear generator [IAE17a]), where electricity demand has grown slowly while *cheap* natural gas and *cheap* renewables have grown fast [War17h]. Consider in particular Three Mile Island, which has been losing money since 2012, and is planning an early retirement in 2019 unless the state of Pennsylvania introduced “needed policy reforms” (probably alluding to the nuclear subsidies in the states of Illinois and New York that keep their reactors open) [Cro17j]. On the other hand, it is a challenge to *shut down*: the limited amount of reliable and comparable information on decommissioning costs [OEC16] is another threat to the nuclear financial vulnerability.

What about the new additions of nuclear generation? In 2016, 1) approximately 66 GW were under construction [IEA17d] (significantly less than the 147 GW that would be retired by 2030 without life extensions [IAE17a]) and 2) construction starts accounted for just 3.0 GW [Aged] (less than the 8.5 GW average of the 2006-2015 period and significantly less than the 20 GW of yearly capacity additions needed to meet the 2DS targets for 2025 [IEA17d]) .

However, low construction rates are not the only threat to new nuclear reactors: poor construction execution is also a threat. Andrew Ward, Energy Editor

at Financial Times, wrote ironically: *“It sometimes seems like US and European nuclear companies are in competition to see which can heap greater embarrassment on their industry”* [War17h].

As for the US, Westinghouse-Toshiba was building the only 2 plants under construction in US soil, the Generation III+ “Plant Vogtle” and “VC Summer”, with years of delays and billions over budget [War17h]. In 2017, these disastrous cost overruns finally collapsed: works were suspended in VC Summer, Westinghouse filed into bankruptcy protection and parent company Toshiba faced serious financial trouble [War17e]. So serious financial trouble that it will inevitably transform the shape of Toshiba as a whole, an industrial giant that has spent more than a century at the heart of Japan’s industrialisation. When Satoshi Tsunakawa, Toshiba’s president, was asked about the reason of Toshiba’s financial downfall, he responded: *“Looking back now, we can’t deny it was the Westinghouse acquisition”* [ILC17].

As for Europe, French AREVA is building two of its new European Pressurised Reactors (EPR, also belonging to the new Generation III+) in European countries: one at Flamanville in France (the only reactor under construction in France [Ageg]) and one at Olkiluoto in Finland (the only reactor under construction in Finland [Ageg]). Both of them are also years late and billions over budget, but *at least* they will likely start operation between 2018 and 2019, delayed 6 years and 10 years respectively [War17h] & [Mil17].

On the public sector side, nuclear energy was almost forgotten in the NDCs of the Paris Agreement (only 10 mention nuclear energy out of 163 submitted at the end of 2016 [IEA17d]) and, at the same time, some governments of the largest nuclear-generating countries are stepping back. The most radical responses have arisen in South Korea and Germany (5<sup>th</sup> and 7<sup>th</sup> largest nuclear generators in the world respectively [IAE17a]), whose governments have announced plans to completely phase out their nuclear fleets by 2060 and 2022 respectively [JA17a] & [Gera].

Less radically but very worryingly, France (2<sup>nd</sup> largest nuclear generator [IAE17a]) will move away from nuclear generation in the near future if Nicolas Hulot, its newly-appointed Energy and Environment minister, is taken seriously. Hulot warned that *“as renewable energy becomes more and more competitive, the nuclear industry business model belongs to the past”* and acknowledged that France should stop using nuclear energy as *“a medium-term target”*. *“While elsewhere the energy transition accelerates, EDF gets closer to AREVA, overinvests in costly nuclear projects like Hinkley Point and does not invest enough in renewables”* [CM17].

A moderate but cold response came from Russia (4<sup>th</sup> largest nuclear generator [IAE17a]), who reduced in 2016 its nuclear growth projections for the coming years as the growth projections of electricity demand were also reduced [IEA17d]. A moderate response, but cold in any case.

Furthermore, international energy institutions do not agree on the role of nuclear energy. The International Atomic Energy Agency (IAEA) proposes two different scenarios for nuclear generation from 2016 to 2050 in its report [IAE17a]. These two scenarios are fundamentally different: the most ambitious (“High case”) estimates 767 GW of gross capacity additions ( $\approx 23$  GW on a yearly basis) so that net nuclear capacity doubles between 2016 and 2050, whereas the least ambitious (“Low case”) estimates only 282 GW of gross capacity additions ( $\approx 8$  GW on a yearly basis) so that net nuclear capacity in 2016 and 2050 are roughly the same.

IEA, which is not necessarily pro-nuclear, considers scenarios as ambitious as IAEA’s “High case”: average gross capacity additions of 20 GW to meet the 2DS targets for 2025 ([IEA17d]) or 24 GW to meet the “66% 2.0°C” targets for 2050, similar to the annual additions in the 1980’s [IEA17c]. In the latter case, IEA assumed that nuclear development *“is led by stronger development in China [...] and India [...] Other long-time leaders in nuclear power generation also expand their fleets in this scenario, as part of their low-carbon strategies”*, which is incoherent with the recent public and private sector reactions outside China and India. This IEA nuclear scenario will *likely* never come true if it relies on this assumption.

IRENA, which again is not necessarily pro-nuclear, apparently contradicts itself in the space of two pages in its report [IEA17c]. In page 141, IRENA estimates investments totalling \$3 trillion in nuclear generation between 2015 and 2050 in the “Reference Case” (shown in its Figure 3.8), but suggests *additional* investments of \$ 1 trillion in CCS, material improvements and nuclear in the more aggressive “REmap” scenario. We assume that the category “CCS & Others” (in its next page) will include CCS and material improvements.

Right after the claim for additional nuclear investments, IRENA states: *“However, there are also avoided investments on fossil fuels in both fossil fuel and nuclear electricity generation capacity as well as in the upstream sector”*. Maybe IRENA was thinking of making smarter investments in nuclear generation (*avoiding* inefficiencies in the “Reference Case” investments) while thinking of a larger overall investment for nuclear generation (avoiding inefficiencies was not enough, nuclear needed *net additional* investments compared to the “Reference Case”).

In page 142 (in its Figure 3.9), IRENA details the aforementioned avoided and additional investments. IRENA *probably* gives  $\approx +\$0.6$  trillion of additional investment for the end-use-sector category “CCS & Others”. I said *probably* because the figure colours are misleading: two categories have almost the same yellow colour and you can hardly distinguish them. You could thus have doubts about whether “CCS & Others” received  $\approx +\$0.6$  trillion of additional investments or no additional investments at all. Placing ourselves in the most pessimistic case for nuclear additional investments, we will assume that “CCS & Others” indeed received  $\approx +\$0.6$  trillion of additional investment.

Therefore, following what IRENA said in page 141, nuclear generation should have received  $\approx +\$0.4$  trillion of net additional investment. Nonetheless, nuclear generation seems to receive a net “additional” investment of  $\approx -\$1.2$  trillion. The difference is \$1.6 trillion less than expected and that difference is too large to be a round-off error... Maybe I understood something wrong, but the IRENA estimates for nuclear energy in [IEA17c] seem contradictory.

As you can see, nuclear energy seems financially problematic for the private sector and misplaced for the public sector. We did not even mention further issues such as nuclear waste, reactor safety or weapon proliferation. It is clear that nuclear energy does not belong with the good. But neither does it belong with the bad. Nuclear energy belongs with the ugly, those forgotten partial solutions that may (or may not) play a role in our carbon-constrained future.

Remember: the good cannot win alone, the bad can help but need time to diversify, the ugly may have something to say. And the energy transition, the best solution to the alarming climate change, cannot afford to give away more time: *we know the direction, the problem now is the urgency*. Each potential forgotten solution must be *urgently* assessed and *urgently* deployed as much as possible. We are full of ideas, empty of time.

We will focus in the following pages on one particular forgotten solution, nuclear energy. Is this ugly energy source, responsible for 1/3 of all low-carbon electricity in the world, something that the energy transition should rescue? Is there room for nuclear energy as a partial solution to this energy transition?

*With today’s technologies, we argue, a 100-percent renewable energy future is an expensive fantasy. And belief in that fantasy can motivate damaging public policy choices, like cutting off support for nonrenewable but equally clean sources of energy, like nuclear power*

*Varun Sivaram, Philip D. Reed fellow for Science and Technology, CFR*

*“A Clean Energy Transition Needs More Technology Options”, [Siv17]*



## Part II

Why are the possible and the actual  
still so far apart for Nuclear Energy?



## Chapter 3

# An energy species in an energy ecosystem

*The report [“Better Energy, Greater Prosperity”] would have been much more useful if the authors had set out the scale of the problem, described the tools available — such as a carbon price or the deployment of carbon capture and storage technology — and then asked why so many of them are not being used. The options for taking action have been clear for the last 20 years and Science and Engineering are gradually reducing the costs of many of the possible steps. The challenge now is not about identifying what could be done, but rather about understanding why the possible and the actual are still so far apart.*

*Financial Times*

*“A utopian misdirection on energy”, [But17h]*

Let’s recap how we come to be here. Where did we start? First, we set out the scale of the problem, climate change, which is definitely real, is definitely derived from human activity and is definitely an alarming problem. Second, we found a genuinely promising solution, an energy transition. In theory, it was a transition in energy quantity and quality that would alleviate climate change through extended decarbonisation of our economy. In practice, conversely, the energy transition is not succeeding: the good renewables cannot win alone, the bad fossil fuels may help but need time to diversify and the ugly forgotten are underestimated. *We know the direction, the problem now is the urgency.* This has been our journey so far.

Now we need to go one step further: we need to solve the urgency problem of the energy transition. This solution cannot be single-piece, since the good cannot win alone. This solution must be multi-piece, like in the Wild West, resorting to the 22 independent technologies that we mentioned in the previous chapter. Currently, 16 out of these 22 independent technologies are potential solutions that are largely underestimated. How do you want to solve the energy transition puzzle, that needs

around 22 pieces, if 16 pieces are missing? Henceforth, we will take one of the missing pieces, nuclear energy, and ask ourselves: “*Why is the nuclear energy piece missing from the energy transition puzzle?*”

With that in mind, we will first delve into the current, fragile situation of nuclear energy. We have already introduced the *symptoms* of this fragility, when we explained in the previous chapter *how* the possible and the actual are still so far apart for nuclear energy. The expensiveness of building, operating and closing. The lack of governmental and international support. Nuclear waste, reactor safety or weapon proliferation were also mentioned in passing. However, we have not spoken yet about the *causes* of this fragility, about *why* the possible and the actual are still so far apart. We will need to raise our vision to address this second issue, since the causes cannot be found by looking *solely* at nuclear energy, but only by looking at nuclear energy *within the framework* of the larger energy ecosystem.

### 3.1 22 Species, 1 Ecosystem, 6 Stakeholders

*As many more individuals of each species are born than can possibly survive; and as, consequently, there is a frequently recurring struggle for existence, it follows that any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected. From the strong principle of inheritance, any selected variety will tend to propagate its new and modified form.*

Charles Darwin

“*On the Origin of Species*”, introduction

Charles Darwin published in 1859 one of his masterpieces, “On the Origin of Species”, giving birth to evolutionary biology. His main contribution, namely evolution by natural selection, connects adaptation to the ecosystem and survival. Individuals who are best adapted to their ecosystem are the individuals with the highest chances of survival.

You can apply Darwin’s ideas to one species (giraffes of larger necks have higher chances of survival during food shortages) or multiple species living in the same ecosystem (species with less water needs have higher chances of survival during droughts). We will even apply Darwin’s ideas to an imaginary energy ecosystem: we will imagine nuclear energy as a living being in an ecosystem, specifically some sort of *energy species inside an energy ecosystem*. As in evolutionary biology, we will see that adaptation to the energy ecosystem and survival are likewise connected. But first, take an inspirational look at Figure 3.1, so that we have the same image in mind to describe the energy species inside the energy ecosystem.



Figure 3.1: “The Garden of Earthly Delights”, detail of the left panel of the triptych, painted by Hieronymus Bosch around 1500. Image from Wikimedia Commons [Bos]

In a nutshell, twenty-two energy species share one energy ecosystem that is shaped by six stakeholders. How could we describe these characters and interactions, keeping “The Garden of Earthly Delights” in mind?

**22 Species** When we speak about “22” energy species, we speak about the “22” independent technologies involved in our sustainable energy transition. They are the good, the bad and the ugly.

Let’s get back, for a moment, to “The Garden of Earthly Delights”. Manifold species inhabit that portrait: some are animals while others are plants, some swim while others fly, some are lovely while others are frightening, some are established while others are migrating, some are nascent (by the lake) while others may only exist in our imagination. All this collection of species is diverse, dynamic and interconnected.

The “22” energy species are as diverse, dynamic and interconnected. First, they are *diverse*, since all of them have their genuine internal technological features. Some are related to energy supply while others to energy demand, some are cleaner while others more reliable and affordable, some are lovely while others are frightening. Second, they are *dynamic*, since the energy species are always evolving and adapting to “the complex and sometimes varying conditions of life”. Some are withdrawing or migrating while others are expanding, some are relative newcomers while others exist mainly in our imagination. Third, they are *interconnected*, because if a new species appears or an old one disappears (both are happening right now, as of November 2017), the whole energy ecosystem could fall into instability.

**1 Ecosystem** When we speak about “1” energy ecosystem, we speak about the “1” energy industry operations and markets as a whole, where the 22 independent technologies interact, thrive and wither. The energy transition is precisely the evolution of this energy ecosystem as a whole.

Let’s get back, for a moment, to “The Garden of Earthly Delights”. I see a portrait of interactions: lush vegetation grows next to the water, water where the ducks swim and the unicorn drinks, water from where the other imaginary creatures emerge, water that emerges from a rosy fountain, birds that rest in this rosy fountain in the foreground, birds waiting for the lion to leave its prey on the hills, birds that live together in the background. And so on, as in any ecosystem, a collection of interactions that are continuously adapting to ensure the equilibrium. All this ecosystem is interactive and adaptive.

The “1” energy ecosystem is as interactive and adaptive. First, it is *interactive*, since the internal technological features of the manifold energy species are complementary. Solar PV and wind energy do not provide the grid reliability that thermal cycles do provide (or that extended energy storage might provide), thermal cycles (in the case of fossil fuels) that should increasingly

incorporate CCS technology to become cleaner, CCS technology that could retrofit industrial applications, industrial applications where energy efficiency is also a target, energy efficiency that must go hand in hand with energy accessibility for low-and-middle income countries.

Second, it is *adaptive*, since the internal technological features of each energy species are adapting to the external energy ecosystem. Coal is plummeting worldwide but is firmly resisting in the countries with the largest coal reserves (remember our Figure 2.9). One of those coal countries is China, where nonetheless the government is incipiently looking beyond coal [PR17] with huge investments in renewables [Cro17g], nuclear energy [Ageg] and energy efficiency [IEA17a]. Unsurprisingly, this Chinese policy coincides with a boom in the Chinese renewable industry ( $\approx 2/3$  of all solar panels and  $\approx 1/2$  of all wind turbines are manufactured in China [PR17]) and with worrying levels of air pollution (“As far back as 2013, the government called air pollution the ‘greatest daily health risk to the people of Hong Kong’ ” [Has17]).

As in evolutionary biology, adaptation to the energy ecosystem and survival are likewise connected. Energy species whose *internal technological features* best match the *external energy ecosystem* are the energy species with the highest chances of survival. It follows that as the energy ecosystem evolves, as the energy transition unfolds, energy species must evolve accordingly.

Lastly, where does the energy ecosystem evolution stem from? On one side, it comes from *endogenous* sources, from the mutation of energy species themselves: “any being, if it vary however slightly in any manner profitable to itself [...] will have a better chance of surviving”. On the other side, it comes from *exogenous* sources, from the mutation of environmental conditions beyond the energy species: “the complex and sometimes varying conditions of life”.

Renewable energy from solar PV and onshore wind exemplifies how endogenous and exogenous evolution can *converge*, such as with steadily diminishing costs ( $-4/5$  for solar panels and  $-1/3$  for wind turbines between 2009 and 2017) accompanied by direct policy support (in around 146 countries at the beginning of 2017, nearly triple the number of 2004) [Cla17a]. Nuclear energy exemplifies how endogenous and exogenous sources can *diverge*, such as designing “less agile” reactors (with long lead times, long payback periods and huge upfront costs) when the financing prefers “more agile” reactors (more modular, with shorter payback periods and smaller upfront costs) [IAE11] & [But17d].

**6 Stakeholders** When we speak about “6” stakeholders of the energy ecosystem, we speak about the “6” stakeholders that shape the energy ecosystem as exogenous sources, “the environmental conditions” to which the 22 independent technologies should better adapt. They are everything but for energy development companies, as we will detail later.

Let’s get back, for a moment, to “The Garden of Earthly Delights”. I see a portrait of interactions, which, in other words, is a portrait of dependencies.

What will happen if water vanishes from the scene or floods the grasslands? What would happen instead if an asteroid collided in the middle of the scene? In each of these scenarios, the dependencies become the clearer: some species will have higher chances of survival than others as a function of their adaptation to the emergent environmental conditions.

Now look again at the original scene of “The Garden of Earthly Delights”. Even in that original scene, without floods nor asteroids, the dependencies are present: swans thrive better in the lake than on the grasslands, elephants thrive better on the grasslands than in the lake. Evidently, environmental conditions favour certain internal features of the species and punish some others, favouring accordingly certain species over some others. Environmental conditions are the external “shaping agents” of the ecosystem.

The “6” stakeholders of the energy ecosystem are precisely the *external “shaping agents”* of the energy ecosystem.

We will start by saying what these external “shaping agents” are *not*. They are not energy *development* companies, which directly *develop* the 22 independent technologies (such as Oil & Gas companies, renewable developers or even research institutions). Precisely, energy development companies are *inside* the 22 energy species, because they are their internal “shaping agents”, their endogenous sources of evolution. So to speak, energy development companies are the *genes* of the 22 energy species.

We will continue by saying what these external “shaping agents” *really* are. We will classify them into 6 categories, inspired by the framework developed by the World Economic Forum and McKinsey & Company [WEF17a]:

1. Energy *management* companies, *managing* energy technologies (such as electric utilities, transmission system operators (TSO) or service companies) but *not developing* the technology
2. Large energy users, mainly belonging to the industrial sector (as wide as chemicals, cement, metals, automotive manufacturing or mining)
3. Financial sector, mainly referring to institutional investors (such as commercial banks or different types of funds) and accredited investors (such as natural individuals, brokers or insurance companies)
4. Policy-makers, either involved in energy legislation or lobbying (such as energy ministries or environmental agencies) or involved in financial regulation
5. International organisations, from the most specialised ones (IEA, IRENA or IAEA) to the most generic ones (United Nations or The World Bank)
6. Civil society stakeholders, which we will mainly understand as “public opinion”



All in all, there are **22 energy species that share 1 energy ecosystem shaped by 6 stakeholders**. As any ecosystem is a network of dependencies between its species and its environmental conditions, the 1 energy ecosystem (energy industry operations and markets as a whole) is a network of dependencies between its 22 energy species and its 6 stakeholders.

On one hand, its species are energy species, the 22 independent technologies involved in the energy transition. Each energy species has its own genes as internal “shaping agents” (its energy development companies) that express themselves in certain internal technological features. On the other hand, its environmental conditions are stakeholders, the 6 external “shaping agents” to which the energy species should better adapt. They are energy management companies, large energy users, the financial sector, policy-makers, international organisations and the civil society.

As the energy ecosystem changes (due to endogenous changes in the energy species or exogenous changes in the stakeholders), the energy transition unfolds. In this ecosystem-wide evolution, **adaptation to the energy ecosystem and survival are connected**. Energy species whose internal technological features best match the external energy ecosystem are the energy species with the highest chances of survival.

## 3.2 The nuclear species: matching and mismatching

*You're an interesting species. An interesting mix. You're capable of such beautiful dreams, and such horrible nightmares. You feel so lost, so cut off, so alone, only you're not.*

*Carl Sagan*

*“Contact”*

We have already mentioned nuclear energy as an illustrative example of how endogenous and exogenous changes can diverge. Its internal technological features regarding cost agility (“less agile” projects with long lead times, long payback periods and huge upfront costs, not to mention the overruns and delays) are diverging from the external energy ecosystem regarding cost agility (“more agile” projects, more modular, with shorter payback periods and smaller upfront costs). In other words, there is a mismatch between nuclear energy and the energy ecosystem in terms of costs, a “species-ecosystem” mismatch in costs, and we will elaborate on it later.

Nuclear energy has 8 internal technological features that are *potentially* matching or mismatching with the external energy ecosystem. As any energy species, its 8 internal technological features (ITF) are, for the most part, *homogeneous* on the global scale. Therefore, we can fairly classify them into potential strengths and

weaknesses on the global scale, as a function of the potential match or mismatch between each ITF and the external energy ecosystem.

On one side, we identify 4 potential strengths, which are its 1) **environmental impacts** (low GHG emissions and low land footprint), 2) **human-health impacts** (low air pollution), 3) **grid security** (dispatchable and provides inertia for the frequency stability of the grid) and 4) **geostrategy** (boosts technology knowledge and exports, limits geopolitical vulnerability) . We identify them as potential strengths, because the external energy ecosystem can potentially value them: a source of climate mitigation, densely concentrated, that favours clean air and energy security. Seen from this perspective, how could we possibly reject nuclear energy?

On the other side, we identify 4 potential weaknesses, which are its 1) **cost** (“less agile” projects with long lead times, long payback periods and huge upfront costs, not to mention the overruns and delays), 2) **safety** (“hard” and “soft” impacts of accidents), 3) **waste** (unresolved long-term disposal of high-level waste) and 4) **proliferation** (threat of civil nuclear technology diverting to nuclear weapons) . In line with the challenges that MIT highlighted [MIT03] & [MIT09], we identify them as potential weaknesses, because the external energy ecosystem can potentially shy away from them: an overly expensive and risky investment that is inseparably connected to catastrophic meltdowns, hazardous waste and mass-destruction weapons. Seen from this perspective, how could we possibly accept nuclear energy?

So what? Should we better accept or reject nuclear energy? A complete, worldwide answer to this question does not exist. As any ecosystem whose environmental conditions vary in space and time, the external energy ecosystem will be *heterogeneous* on the global scale and nuclear energy will fit better in some regions and worse in others. As any species (or, in proper biological terms, as any *genus* of closely-related species) whose genes slightly vary (between any two species in that genus), the internal technological features (mainly regarding costs) may accordingly vary on the global scale. We must forgo a complete, worldwide answer to find partial, regional answers instead. Partial, regional answers do exist.

Let’s perform now a simple experiment to sense this disparity. Three questions, answer each one before reading the next one. First, in which country do you live? Second, with which stakeholder do you identify the most inside the energy ecosystem? (at least, remember that you are a civil society stakeholder). And third, which are the first 3 words that come to your mind when you hear “nuclear energy”?

Answers to this third question are everything but homogeneous, highly dependent on the previous two answers. Instinctive reactions towards nuclear energy will be geographically heterogeneous (do you live in China or in Japan?, do you live in France or in Germany?) and stakeholder-wise heterogeneous (are you an investor or a TSO employee?, are you policy-maker or a civil society stakeholder?). Nuclear

energy may display relatively homogeneous ITF, but is facing fairly heterogeneous responses. We could have perfectly foreseen this: one size does not fit all.

The geographical stakeholder preferences mainly justify this disparity. We have over and over insisted on the word *potential* when describing the ITF. The 4 potential strengths and 4 potential weaknesses are latent everywhere, but manifest to a higher degree in some places than in others as a function of the geographical stakeholder preferences. May certain policy-makers be more worried about existing air pollution and land constraints than about future nuclear waste? May civil society stakeholders be as worried about climate change as about nuclear accidents? For each geography and for each country, a different balance, a different answer. *Do the manifest strengths outweigh the manifest weaknesses in this particular country?*

This is precisely the right focus: manifest strengths versus manifest weaknesses, on the national scale. Causation lies beneath: the global level (globally, why the possible and the actual for nuclear energy are still so far apart) is explained by the regional level (regionally, why nuclear energy is migrating from the West towards the East), which in turn is explained by the national level (nationally, why some countries are for or against nuclear power). Our analysis gradually travels the same path. First, from the global deficit towards the regional polarisation. Second, from the regional polarisation towards the national balances.

In short, nuclear energy has 8 internal technological features that are fairly *homogeneous* worldwide (as any species whose genes hardly vary in space and time). 4 of the features are potential strengths (environmental impacts, human-health impacts, grid security and geostrategy) while the other 4 are potential weaknesses (cost, waste, safety and proliferation). In parallel, the external energy ecosystem is fairly *heterogeneous* worldwide (as any ecosystem whose environmental conditions vary in space and time). Thus, the potential features manifest to a different extent in each region, in each country. These **national balances between manifest strengths and manifest weaknesses** determine the survival perspectives of nuclear energy.

Now comes the hard part: how does this conceptual framework apply to the real world? Again turning to Biology, our analysis travels from the symptoms of an apparently unitary disease towards its ultimate, disparate biological causes.

*Cancer is not a disease but a whole family of diseases. These diseases are linked at a fundamental biological level. They're characterised by the pathological proliferation of cells - occasionally cells that don't know how to die, but certainly cells that don't know how to stop dividing [...] But although there's a deep commonality between prostate cancer, breast cancer, leukemia, although they're connected at the cellular level, every cancer has a different face.*

*Siddhartha Mukherjee*

*"The Emperor of All Maladies: A Biography of Cancer", interview with the author*

### 3.3 Beneath the world: a regional polarisation

Let me remind you *how* the possible and the actual for nuclear energy are still so far apart worldwide. Nuclear energy should ideally account for 5-6% of overall CO<sub>2</sub> reductions in IEA scenarios, but worldwide public and private sectors are nowhere near there. Remember the Paris Agreement’s NDCs (only 6% mentioned nuclear energy), the radical reactions of nuclear strongholds such as South Korea, Germany and France (phasing out or shying away from nuclear energy) or the fragile projections for nuclear strongholds such as the US (whose reactors are aging and financially struggling) and Russia (who has reduced its nuclear growth projections).

Construction starts are simultaneously falling behind (Figure 3.2). Focusing on the 6 years before and after Fukushima (2011), the average construction starts have diminished from 8.8 GWe (between 2005 and 2010) to 5.9 GWe (between 2012 and 2017). The latest years are scoring even worse: only 3.0 GWe started construction in 2016 and 3.3 GWe in 2017 (in parallel, 2.2 GWe suspended construction in 2017, yielding only 1.1 GWe net construction starts) [IAE17b] & [Aged].

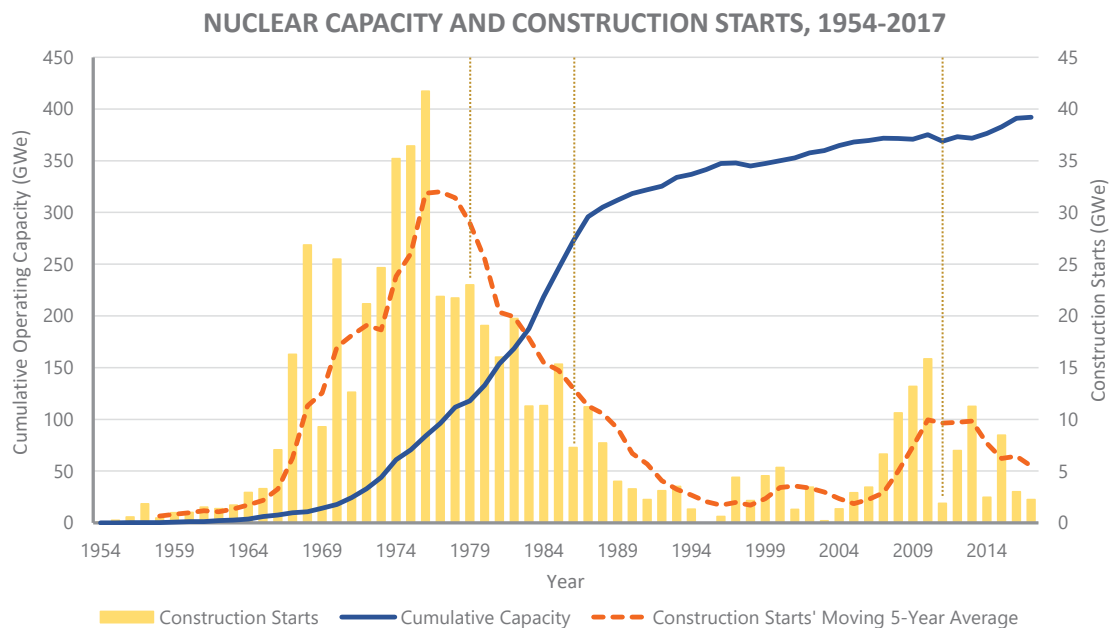


Figure 3.2: Nuclear cumulative operating capacity and construction starts, expressed in net electrical GWe. Construction boomed between the late 1960’s and early 1980’s. Its decline coincided with two accidents: 1979’s Three Mile Island (US) and 1986’s Chernobyl (present-day Ukraine). Afterwards, a nuclear “renaissance” was taking off in the late 2000’s, but vanished coinciding with another accident, 2011’s Fukushima (Japan), and the dawn of the renewable boom. Averaged construction starts have naturally decreased since then. Data from IAEA [IAE17b] & [Aged]

The recent policy and construction trends call IAEA’s and IEA’s nuclear scenarios into question. Their most ambitious scenarios assume 20 GWe of yearly gross additions until 2025 (IEA’s 2DS) or approximately 23-24 GWe of yearly gross additions until 2050 (IAEA’s “High case” and IEA’s “66% 2.0°C”). These nuclear scenarios seem disconnected from reality and this disconnection partially jeopardises the feasibility of our most ambitious energy transition, that aimed to limit the rise in average global temperature to 2.0°C throughout the 21<sup>st</sup> century.

On one hand, recent construction trends tear **short-term nuclear targets** down. What should the world do to achieve the 20 GWe of yearly gross capacity additions until 2025? Let’s imagine the most optimistic pathway.

First, let’s assume that the gloomy years for nuclear energy before 2018 do not raise the need for yearly gross capacity additions until 2025. This implies that 160 GWe should come online between 2018 and 2025, both inclusive. Second, let’s assume that all capacity that is currently under construction (as of December 2017) comes online before 2025. No delays, no suspensions. This implies that 60 GWe would come online no later than 2025 and thus 101 GWe would need to start construction. Third, let’s assume the most optimistic construction times, which are 5.3 years per 1 GWe of net electrical capacity (achieved in the Far East, as detailed in Figure 3.8). This implies that only constructions started before September 2020 would be online by December 2025 and therefore all to-be-started construction (100 GWe) should start between January 2018 and August 2020 (32-month period).

In order to homogenise the workload, 3.1 GWe should start construction monthly between January 2018 and August 2020 (or, in yearly terms, 37.5 GWe per year). This yearly construction start of 37.5 GWe has been achieved only once in history (41.7 GWe in 1976 [IAE17b]) and is more than 6 times the yearly average between 2012 and 2017. What makes matters worse is that this pathway is the most optimistic that we could imagine. Consequently, it seems quite impossible to achieve the 20 GWe of yearly gross capacity additions between 2018 and 2025. Nuclear is not going to reach the IEA’s 2DS targets for 2025 and IEA politely anticipates this disenchantment: *“Improvement, but more efforts needed”* [IEA17d].

On the other hand, recent construction *and policy* trends tear **long-term nuclear targets** down. IAEA’s and IEA’s nuclear scenarios rely on the roles of relative newcomers, such as China or India, as well as long-standing leaders. Take IEA’s “66% 2.0°C”, which assumes that *“Other long-time leaders [besides China and India] in nuclear power generation also expand their fleets in this scenario, as part of their low-carbon strategies”* [IEA17c]. Take now IAEA’s “High case”, which assumes that *“the Far East will see the biggest expansion, especially in China and the Republic of Korea, while India is leading the expansion in the Middle East and South Asia. There is also sizeable potential for nuclear expansion in the Russian Federation”* [IAE16].

China deserves an introductory mention here. Look first inside the Chinese borders: more than 1/4 of the worldwide under-construction capacity is currently built in China (17 GWe out of 60 GWe), almost as much as in the four closest followers altogether (Russia, the UAE, South Korea and India) [IAE17b] & [Aged].

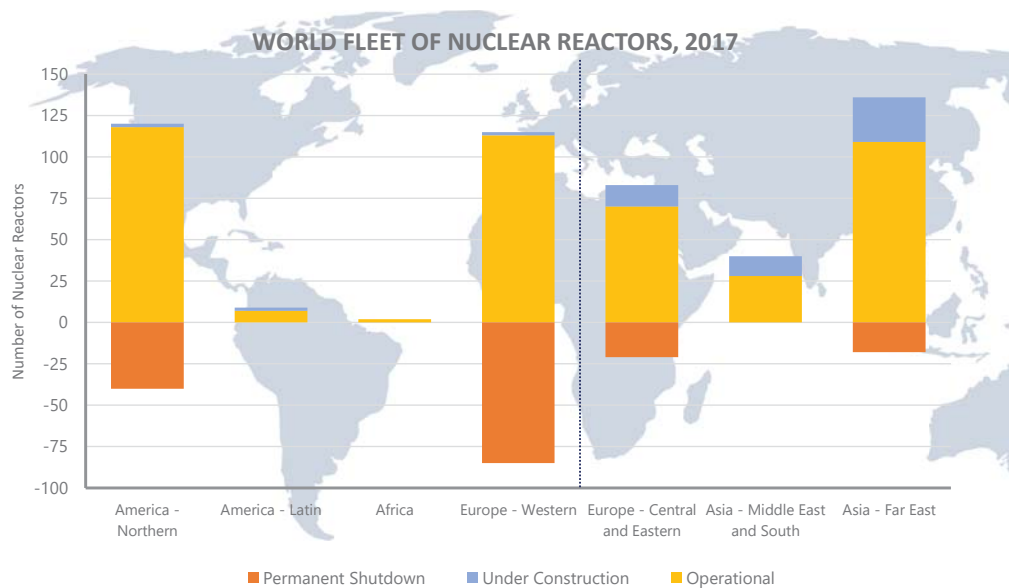
Look now beyond the Chinese borders: China is exporting Chinese nuclear technology. Chinese companies are building reactors in Pakistan and Romania, are scheduled to build reactors in Argentina, the UK and Iran, are bidding for further projects in Turkey, South Africa and Saudi Arabia and are discussing preliminary deals in Kenya, Egypt, Sudan and Armenia [Cot17a]. As we will develop later, this decision makes at once all the geostrategic sense, since 8 out of these 12 countries are involved in China's "*One Belt, One Road*" gargantuan initiative to foster trade by fostering road, rail and energy projects [FKCB16] & [oBP].

IEA and IAEA assume however that China's success is not enough, it must be accompanied by other successes. The successes of other "long-standing leaders", such as the US and Canada, France, Germany and the UK, Ukraine and Russia, Japan and South Korea. These 9 "long-standing leaders" are leading the worldwide nuclear generation (3/4 of the worldwide total in 2016), but will likely fall behind soon because their fleets are aging (on average, 9 more operational years compared to non-long-standing leaders) and have no comparable replacements in sight. These 9 countries *altogether* are building only slightly more as China *alone* [IAE17b] & [Aged].

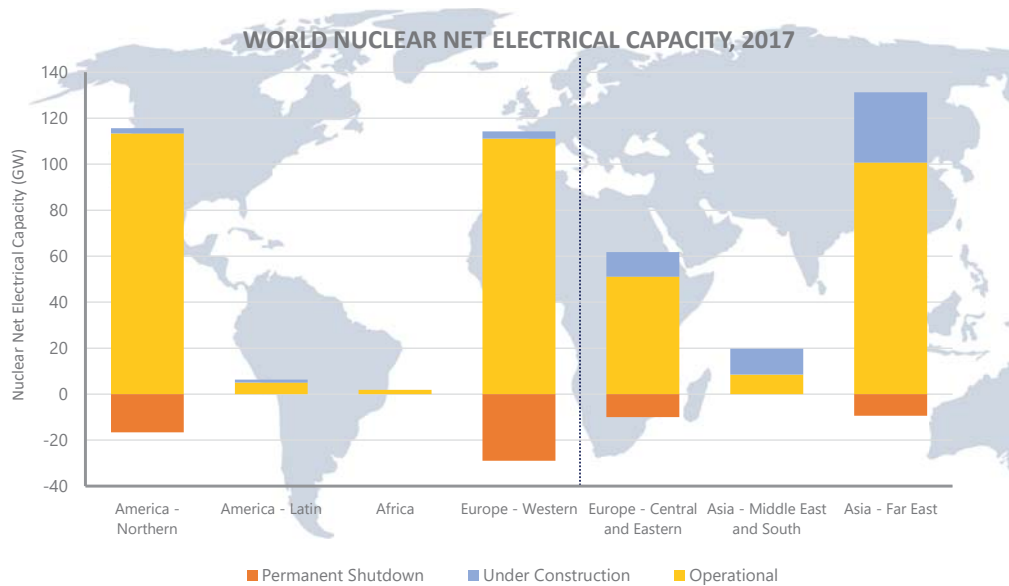
Policy news for each of them are not any better than for the whole of them. Some of these 9 "long-standing leaders" are openly opposing nuclear generation: Germany and South Korea promised to phase out nuclear energy in 2022 and in 2060 respectively, whereas France should stop using nuclear energy as "*a medium-term target*" in the words of its energy and environment minister. Some of the 9 are struggling with nuclear finances and replacement, such as the US and the UK. Some of the 9 are readjusting their nuclear expectations, such as Russia after reduced projections of electricity demand growth and Japan after Fukushima (only 5 of the 42 Japanese operable reactors have restarted operation, while 21 are awaiting restart approval [Assd]).

We will analyse these 9 "long-standing leaders" on the individual scale later, but their overall panorama is gloomy compared to IAEA's and IEA's most ambitious scenarios. Their altogether, *recent* additions have been very weak (an average of 1.3 GWe between 2000 and 2017 [IAE17b] & [Aged]), only 6% of the ideal yearly figures of 23-24 GWe until 2050. However, their *future* additions might be even lower (due to the nuclear-free policies) or dubious (due to the remaining nuclear-uncertain countries). These 9 "long-standing leaders" will leave a void and there is no way that China and India can entirely fill it. Therefore, nuclear will most probably not reach IAEA's and IEA's 2050 targets.

It feels like “*myth busting*”. Nuclear energy will doubtlessly not reach the 2025 targets and will most probably not reach the 2050 targets of IAEA’s and IEA’s most ambitious scenarios. But *why* are the possible and the actual still so far apart? The first layer of the answer resembles the distinction between relative newcomers and long-standing leaders, but in strictly geographical terms: **two different sides of the world are pulling in two different directions**. Take an introductory look at Figure 3.3. The global energy ecosystem is polarised: nuclear energy is withering in the West and thriving in the East, the nuclear species is “migrating” from the West towards the East.



(a) World nuclear fleet, in number of reactors per region and status



(b) World nuclear capacity, in net electrical GWe per region and status

Figure 3.3: World nuclear fleet and capacity, showing a leading but diminishing trend in the West and a soaring trend in the East. Status as of November 2017. Data from IAEA [Agee], [Agef] & [Ageg], Worldmap image from Openclipart [Sho]

As Figure 3.3 introduces, our global energy ecosystem is polarised concerning the past, present and future of the nuclear species. With an air of Cold War’s days but with shifted roles, the two contrasting sides are *the decaying West* (namely America and Western Europe) and *the booming East* (namely Central and Eastern Europe and Asia). Africa lies somewhere in between, with a minimal role until now (only 2 operational reactors, with none under construction or shut down [IAE17b]), although we will find incipient polarised reactions between Western Africa and Eastern Africa as well. Oceania lies nowhere so to say, with nonexistent nuclear power until now and no reactors planned for construction [IAE17b].

**The West** encompasses no relative newcomers and several long-standing leaders such as the US, Canada, the UK, France and Germany among others. Take just these 5 countries, which are the most representative of the region. They led in the past, “the fossils tell us”, because they concentrate 2/3 of worldwide shut down reactors [Agef]. The lead in the present in nuclear generation (3/5 of the worldwide total in 2016), but will their fleets are aging (on average, 12 more operational years compared to non-long-standing leaders) [IAE17b]. They will not lead in the near future, since their fleets have no comparable replacements in sight (6 out of the 58 reactors under construction worldwide [Ageg]) and their policy and financial situations are daring for nuclear energy.

Other traditionally nuclear countries in the region, such as Sweden, Spain or Belgium, are not performing any better: 36 years of average operation and not a single reactor under construction [IAE17b] & [Ageg].

**The East** encompasses all relative newcomers, with the leadership of China and India, and another several long-standing leaders such as Ukraine, Russia, South Korea and Japan. The East is comparatively young, especially Asia (only 19 years of average operation [IAE17b]), and will become comparatively even younger, because the East is building 52 out of the 58 reactors under construction worldwide [Ageg]. Eastern boom is gathering pace, but started long ago: between 1993 and 2017, the East connected 5.4 times as much net electrical capacity as the West [IAE17b]. Additionally, Eastern long-standing leaders are staying ahead of its Western counterparts: 27 years of average operation compared to 35 [IAE17b], 15 reactors under construction compared to 4 [Ageg].

**Africa** lies somewhere between the West and the East. Hitherto, Africa has played a minimal role in nuclear energy, with just 2 reactors in operation. In the coming years, China’s overseas influence may change the picture for Eastern Africa (Chinese companies are bidding for projects in South Africa and are discussing preliminary deals in Kenya, Egypt and Sudan), while Western Africa remains away from nuclear. However, China’s nuclear influence in Africa is only incipient. We will hence leave Africa aside for the time being when speaking about the West or the East.



The global energy ecosystem is polarised. The nuclear species is “migrating” from the West towards the East: 35 years of average operation compared to 23, 6 reactors under construction compared to 52 [IAE17b] & [Aged]. Let’s now dig deeper into the migrating trend by segmenting the Figure 3.2 according to **Eastern and Western contributions**. Figure 3.4 shows the *absolute* regional contributions (in GWe), whereas Figure 3.5 shows the *relative* regional contributions (in % of yearly global contributions). Notice that Figure 3.5 starts in 1963 to avoid nervous oscillations due to minimal changes in the very first years of nuclear development.

The migration has been consolidating for long. The West dominated construction until the late 1970’s, until Three Mile Island and Chernobyl turned the tables around. Between 1979 and 1993, Western construction literally vanished and 53 of its reactors under construction were cancelled (38 of them in the US), whereas only 14 reactors under construction were cancelled in the East (almost exclusively in Central and Eastern Europe). Consequently, Western cumulative capacity hit a plateau in the early 1990’s. Simultaneously, the East took over construction in the late 1980’s and continues to dominate after Fukushima (only 4 reactors under construction were cancelled, exclusively in Central and Eastern Europe).

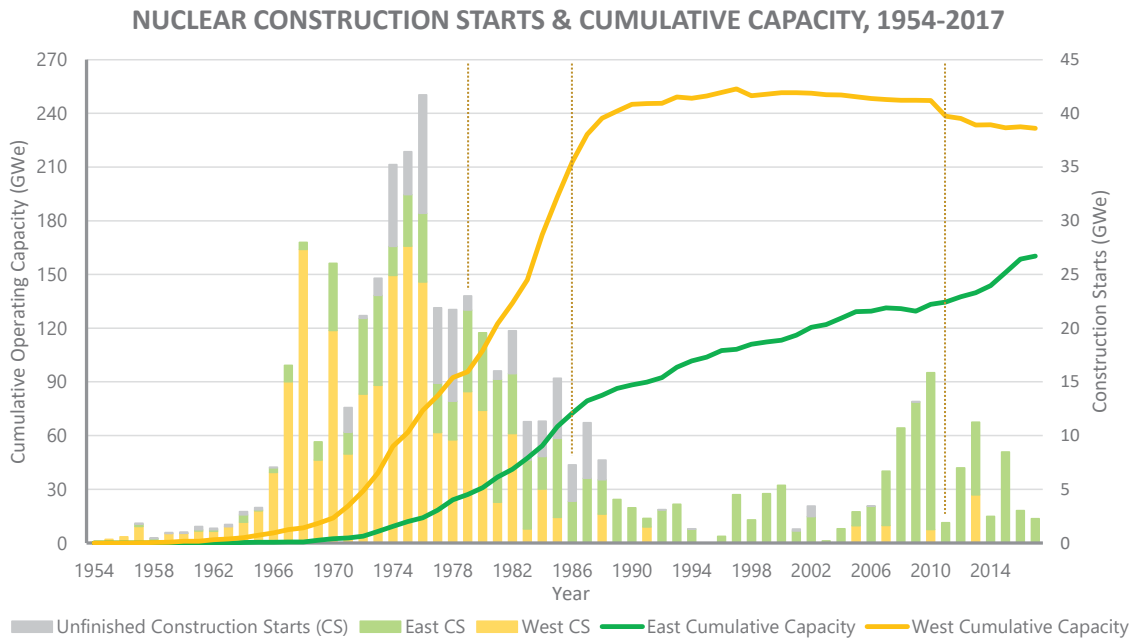
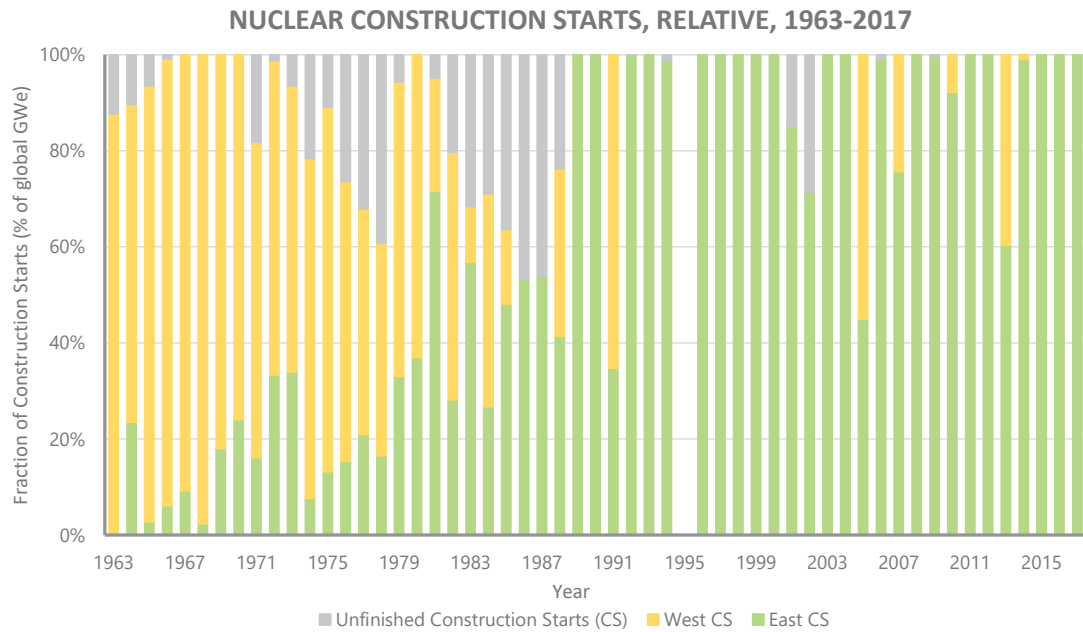
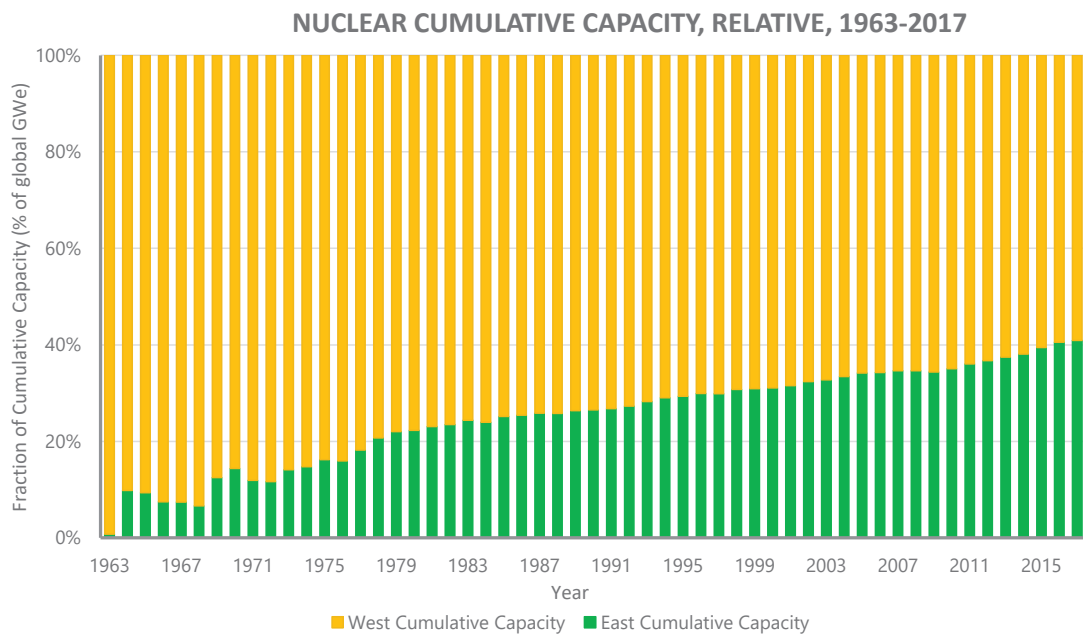


Figure 3.4: Nuclear cumulative operating capacity and construction starts, expressed in net electrical GWe and segmenting according to Eastern and Western contributions. Unfinished construction starts embrace all projects that started construction but were cancelled before completion. The recent suspensions of Summer-2 and Summer-3 in the US are not yet included in this category, since they could still restart [War17], as it recently happened with Shin-Kori 5, suspended in July 2017 and restarted in October 2017 [Aged]. Data from IAEA [IAE17b] & [Aged]



(a) Nuclear construction starts per region, in % of global GWe starting construction each year



(b) Nuclear cumulative capacity per region, in % of global GWe of cumulative capacity each year

Figure 3.5: Nuclear construction starts and cumulative capacity respectively. The West dominated construction starts until the late 1970's, when the nuclear accidents in Three Mile Island and Fukushima struck the US and Europe. The East has dominated construction starts since the late 1980's until nowadays. The all-through consistency of the East is reflected in its steadily increasing share of worldwide cumulative capacity, exceeding today 40% of the worldwide total. Data from IAEA [IAE17b] & [Aged]

The shift in construction starts is reinforced by two other indicators: the number of shut down reactors (3/4 in the West and 1/4 in the East with respect to the worldwide count [Aged]) and the operational years of still operational reactors. We will delve into the second indicator in broader terms, into the different “times” in reactor lives: only operational lives in Figure 3.6, operational together with construction lives in Figure 3.7 and only construction lives in Figures 3.8 and 3.9.

First, let’s focus on reactor **operational lives** as depicted in Figure 3.6, segmenting by status (shut down or operational) and region (East or West, but only for the operational reactors). Look at the “population pyramids” of Eastern and Western reactors: while Eastern reactors are fairly homogeneously distributed across the year clusters, Western reactors are concentrated in the older clusters (mainly between 28 and 47 years). *“Living” reactors are younger in the East.*

Besides, shut down reactors have historically lived longer in the East (on average, 5 operational years more [IAE17b] & [Aged]). *“Deceased” reactors lived longer in the East.* Besides, remember that reactors are under construction mainly in the East (52 out of 58 reactors). *“Nascent” reactors will be born in the East.* Now combine the 3 facts: “nascent” reactors will be born in the East, “living” ones are younger in the East & “deceased” ones lived longer in the East. The conclusion is clear: Eastern share of worldwide cumulative capacity will grow in the coming years.

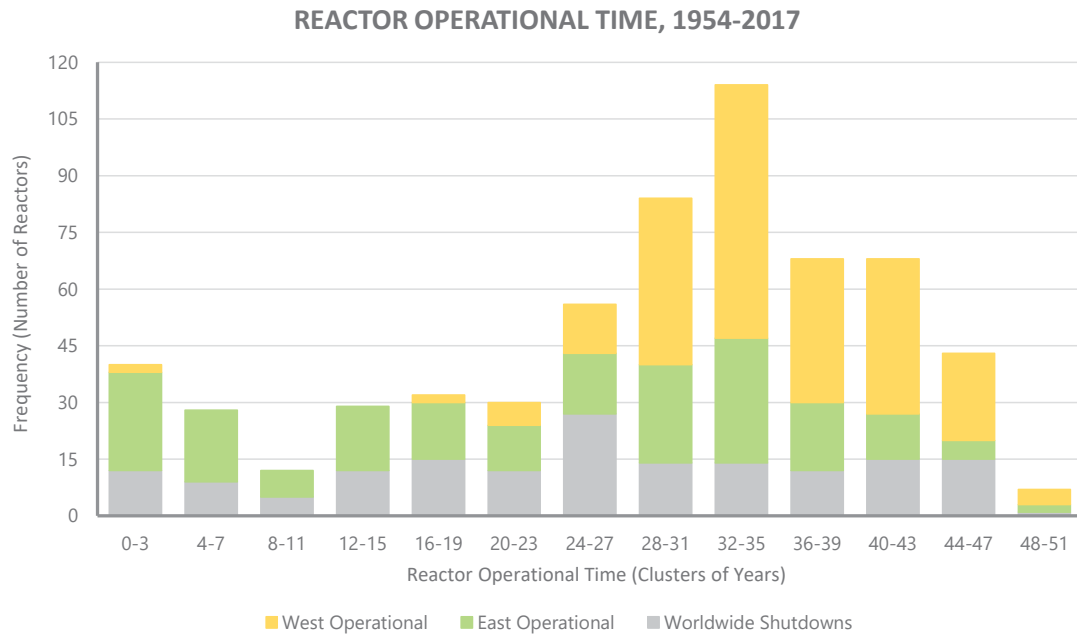


Figure 3.6: Nuclear reactor operational time, in years since the first connection to the grid until its shutdown (for shut down ones) or until December 2017 (for operational reactors). Operational times are fairly homogeneous in the East, fairly aged in the West. Data from IAEA [IAE17b] & [Aged]

Second, let's focus on **operational and construction lives** of operational reactors as depicted in Figure 3.7, segmenting according to IAEA's regions. We have already analysed in Figure 3.6 that “living” reactors are younger in the East if we measure “age” as “operational age”. Figure 3.7 confirms this conclusion: “living” reactors are younger in the East and especially younger in Asia (an average of 19 operational years per reactor, almost half of the values for North America).

Furthermore, Figure 3.7 gives new insights: if you measure the “combined age” (construction and operation) of the regional fleets, the further you travel eastwards, the younger the reactors are. The Far East leads in youthfulness in both indicators: 5 years of construction, 19 years of operation. There is a stark contrast between the extremes in the scale: reactors in the Far East have 21 years less of average combined age compared to the reactors in North America. Combined age shows overall the same West-East divide as operational age (at first sight, construction times seem more or less homogeneous, except for the slowness in Latin America and the swiftness in the Far East), but emphasises the leadership of the Far East also in construction times per reactor.

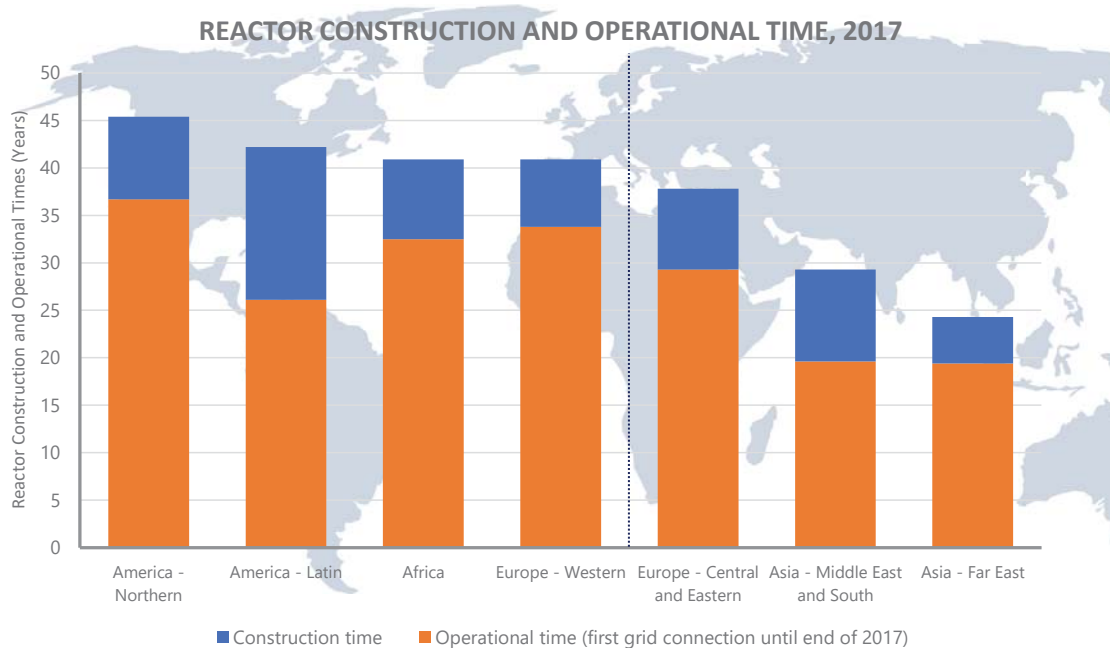


Figure 3.7: Nuclear reactor construction time (since the start of construction until the first connection to the grid) and operational time (since the first connection to the grid until December 2017), expressed in years. Only operational reactors are considered. The further you travel eastwards, the younger the reactors are (with respect to their construction start). Data from IAEA [IAE17b] & [Aged], Worldmap image from Openclipart [Sho]

Third, let's focus on **construction lives** of mainly operational reactors in Figures 3.8 and 3.9. You might argue that the use of construction times *on a reactor basis* is misleading, because we might be comparing apples with oranges: larger reactors (in terms of net electrical capacity) would intuitively take longer to build than smaller reactors. You might hence argue that we should use construction times *on a net electrical capacity basis* to compare apples with apples.

That is precisely what we do in Figure 3.8, which represents the actual construction times *on a reactor basis* and normalised construction times (NCTs) *on a 1 GWe basis*, segmenting according to IAEA's regions. The Far East solidly retains its leadership position in both indicators: it builds large reactors (averaging over 0.9 GWe per reactor) in short times (averaging less than 5 years per reactor). However, the regional tables are turned with respect to Figure 3.7: the West *as a whole* has historically outperformed the East *as a whole* in NCTs.

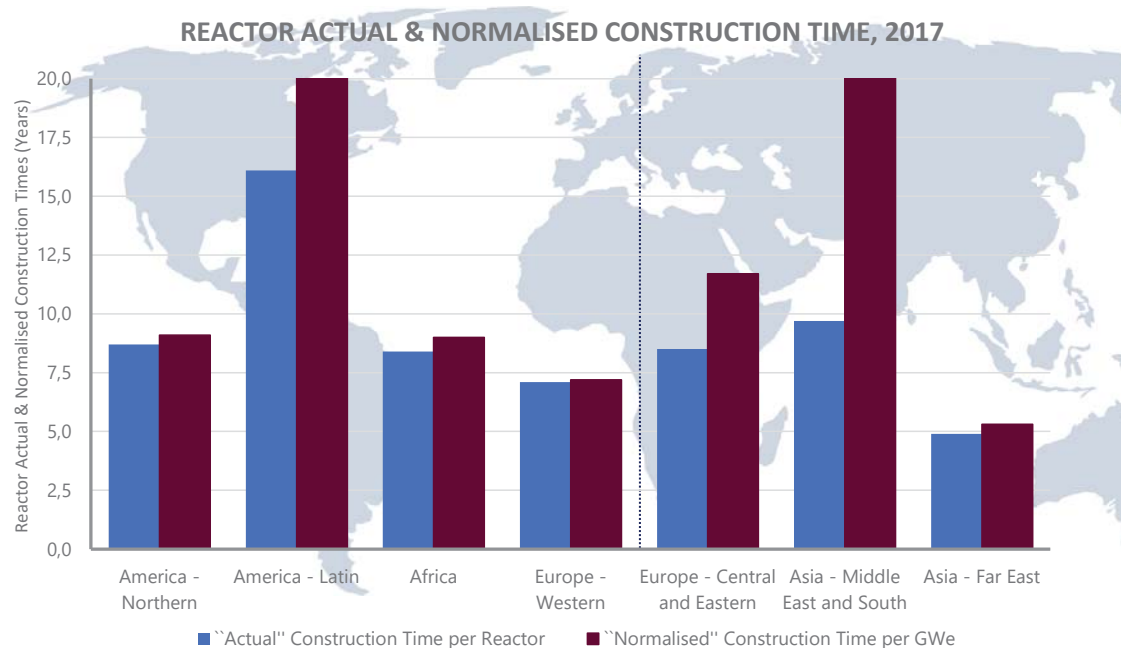


Figure 3.8: Nuclear reactor actual construction time (since the start of the construction until the first connection to the grid) and normalised construction time (for each IAEA region, average actual construction time divided by its average net electrical capacity in GWe). The normalised construction time is a division of averages (not a division of individual values that are later averaged) so that very small or experimental reactors do not severely distort the results. Only operational reactors are considered. Two regions overflow the scale: Asia - Middle East & South (32 years per GWe) and America - Latin (22 years per GWe). Data from IAEA [IAE17b], [Ageg] & [Agee], Worldmap image from Openclipart [Sho]

However, Western regions (without Latin America) score better in NCTs than Eastern regions (without the Far East) due to historical inertia, *not* due to recent trends. Figure 3.9 evidences this contrast between short-term and long-term trends in NCTs: the West led at the beginning, but the East is leading lately.

Western NCTs “learnt” faster and earlier, translating into a faster and earlier scalability that is *still* reflected in Western dominance of cumulative capacity. However, its past scalability is presently compromised: no GWe started construction between 1992 and 2004 and only 9.0 GWe between 2005 and 2017, but are all either suspended or plagued with delays and cost overruns.

Eastern NCTs lagged behind for decades (except in the Far East), accompanied by smaller construction starts in the early years of nuclear expansion. However, Eastern NCTs have been “learning” in a progressive and swinging fashion, until approaching in the 2010’s the Western historical best (around 6 years per GWe). If this overall trend continues, “nascent” reactors will be born in the East, *not only in higher number, but also with higher speed*.

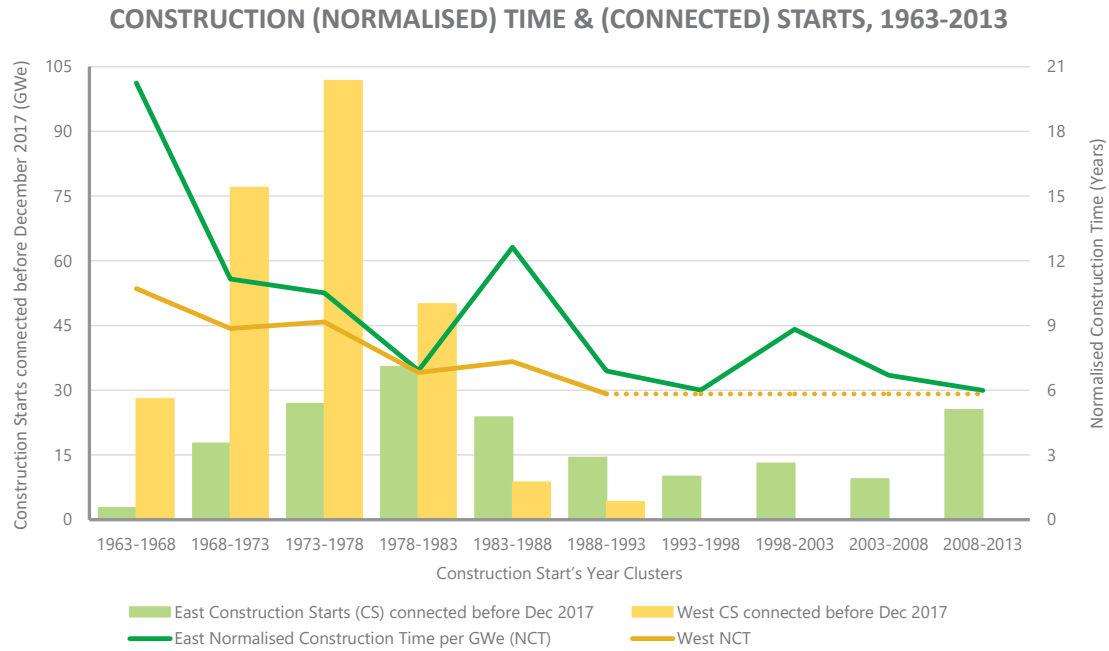


Figure 3.9: “Connected” construction starts (started *during* each year cluster, connected to the grid *anytime* before December 2017), expressed in GWe, and normalised construction times (actual construction times for the “connected” construction starts adjusted for a net electrical power of 1 GWe), expressed in years. Operational and shut down reactors are considered. Changing the clustering patterns typically yields the same conclusion: the West has scaled faster in historical terms, but the East is closing the scalability gap. Data from IAEA [IAE17b] & [Aged]

In essence, two different sides of the world are pulling in two different directions. **Nuclear energy as energy species is migrating from the West towards the East.** “Nascent” reactors will be born in the East in higher number and with higher speed, “living” reactors are younger in the East and “deceased” reactors lived longer in the East. Precisely this polarisation explains *why* the possible and the actual are still so far apart for nuclear energy on the global stage: nuclear energy is withering in the nuclear-leading half of the world, whereas it is -only slowly- gathering pace in the nuclear-emerging half of the world.

Once we have identified this polarisation, we will delve into the West and the East separately. The nuclear species is matching better the Eastern energy ecosystem because nuclear’s manifest strengths are outweighing nuclear’s manifest weaknesses in Eastern countries, even if Eastern national balances differ greatly one from another. Western countries tell the opposite regional story.

Where is the West of the 1970’s, when an average 16.7 GWe started construction each year, but that nowadays in 2017 has the same cumulative capacity as in 1987? Why is the East expanding, doubling its cumulative capacity in 2017 compared to 1987, but expanding slowly? [IAE17b] & [Aged] These are the next two questions beneath the regional polarisation: *what is beneath the East?*, *what is beneath the West?*

*Oh, East is East and West is West, and never the twain shall meet,  
Till Earth and Sky stand presently at God’s great Judgment Seat.  
Rudyard Kipling  
“The Ballad of East and West”*

### 3.4 Beneath the East: Eastern countries' balances

The East encompasses multiple long-standing leaders (namely South Korea, Japan, Russia and Ukraine) as well as all the relative newcomers (led firstly by China and secondly by India). Nonetheless, this distinction between long-standing leaders and newcomers does *not* explain why some countries have staked on nuclear energy. That explanation is our quest now. It lies in the Eastern national balances: the better the matches between nuclear internal technological features and the external energy ecosystem, the better the chances of survival. Remember: manifest strengths versus manifest weaknesses, on the national scale.

These national balances, albeit diverse, show common patterns. These common patterns allow us to classify Eastern national balances in three geographical clusters (Figure 3.10): the *Far Eastern small states* (Japan, South Korea and Taiwan), the *Asian emerging superpowers* (China and India) and the *former USSR states* (Russia, Ukraine and Belarus). These three clusters summarise the East: they account for  $\approx 90\%$  of its reactors and net electrical capacity in operation and for  $\approx 80\%$  of its reactors and net electrical capacity under construction [IAE17b] & [Ageg]. The East: 3 clusters & 8 countries.

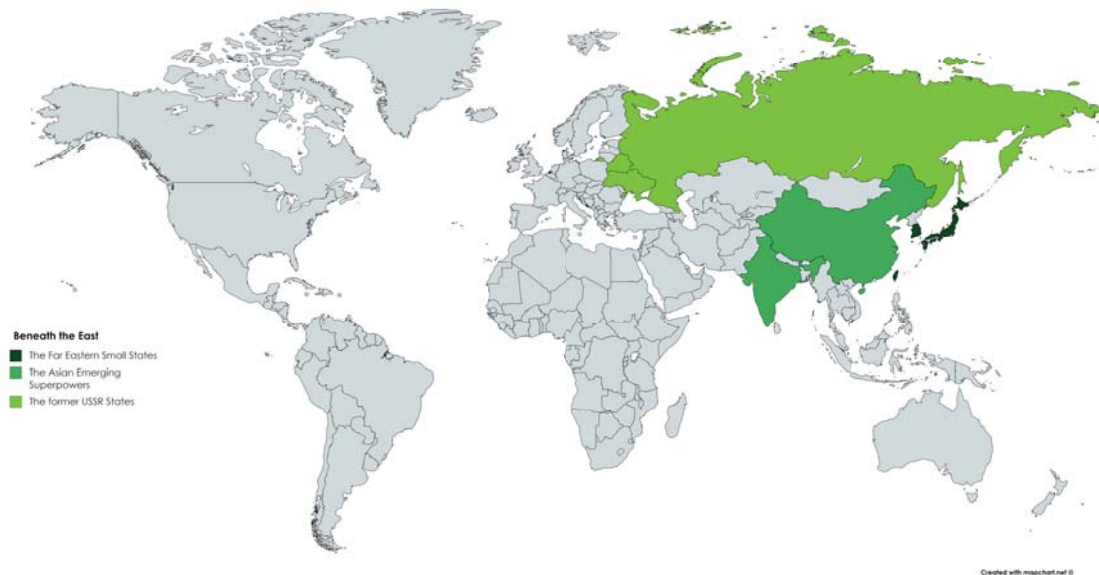


Figure 3.10: Three geographical clusters of national balances in the East: the Far Eastern small countries (Japan, South Korea and Taiwan), the Asian emerging superpowers (China and India) and the former USSR states (Russia, Ukraine and Belarus). There are 10 more Eastern nuclear countries with minor roles, not highlighted in this graph and not individually covered in the following analysis. Map created with MapChart [Map]



Let's delve into the East, into these three clusters. We will discover that one of them indeed values the environmental impacts of nuclear energy, but only regarding the low land footprint, *not* the low GHG emissions. The latter strength is latent everywhere, but has not driven nuclear development anywhere (neither in the East nor in the West). The energy transition as a whole may promote nuclear energy because of its low GHG emissions, but individual countries will not: nuclear energy has less to do with their climate morals and more to do with their national needs.

*It is not from the benevolence of the butcher, the brewer, or the baker that we expect our dinner, but from their regard to their own interest. We address ourselves, not to their humanity but to their self-love, and never talk to them of our own necessities but of their advantages.*

*Adam Smith*

*"The Wealth of Nations"*

### 3.4.1 The Far Eastern small states

Japan, South Korea and Taiwan are small, isolated states with large, foreign energy needs. As for their geography, they are small *islands*: Japan and Taiwan are physically islands, while South Korea is virtually an island (it occupies the southern half of the Korean Peninsula and only borders with its hostile, northern counterpart). As for their energy, they have large energy needs, but small or non-existent domestic energy resources. They are largely dependent on international energy imports and, in parallel, are inclined to dense energy forms (*small* states, *huge* energy needs). These external features match with two nuclear internal strengths: **low environmental impact** (low land footprint) and **geostrategy** (limits geopolitical vulnerability).

On one side, the Far Eastern small states must generate as much energy as possible with minimum land footprint (i.e. with maximum energy density). This is nuclear's first manifest strength: nuclear lifecycle density is among the highest of all energy sources [CH16] & [PBO<sup>+</sup>14] and nuclear electricity density is even significantly higher ("Mining" accounts for 2/3-3/4 of the lifecycle figure [PBO<sup>+</sup>14]). In this regard, Kirill Komarov, from ROSATOM's Management Board, remarked that one 1200-MW nuclear reactor with a land use of 1 km<sup>2</sup> provides the same power as a wind farm the size of Andorra and a solar farm the size of Copenhagen [Foy17].

In parallel, the Far Eastern small *islands* cannot import electricity. Only 2% of worldwide electricity is internationally exchanged [IEAf], but in particular 0% for Taiwan, South Korea and Japan [75]. Would South Korea import electricity from North Korea, Taiwan from China, Japan from Russia?... They must generate all their electricity. With the least land footprint. This is why Taiwan, South Korea and Japan display some of the largest electricity densities in the world (Figure 3.11).

# NATIONAL ELECTRICITY DENSITY, 2016

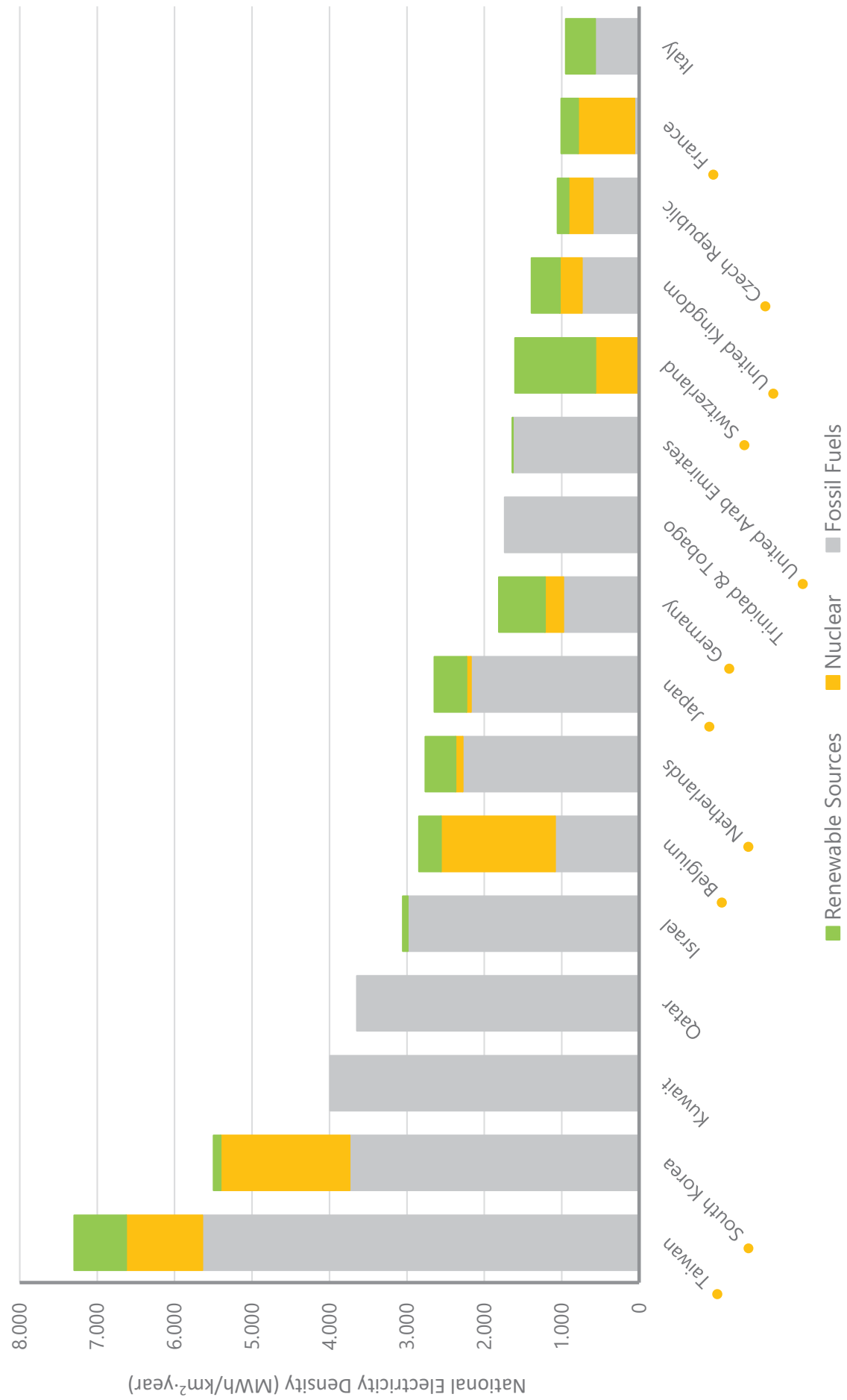


Figure 3.11: Density of electricity generation, in yearly MWh per km<sup>2</sup> of surface. We computed it for 2016 for the 66 individual countries in [BPS17] (91% of worldwide electricity) and we depict it for the top quartile. 11 out of the 31 nuclear countries in [BPS17] are in the top quartile. Singapore ranks first, with 71700 MWh/km<sup>2</sup>·year (97% from fossil fuels, 3% from renewables), not represented to prevent scale overflow. Japan's 2016 nuclear contribution was 1/16 of 2010's. Electricity generation data from BP [BPS17], surface data from The World Bank [WBS] and Encyclopedia Britannica [KWC], nuclear electricity shares from IAEA [IAE17b] and Taiwan's Ministry of Economic Affairs [BoEa], fossil fuel shares from The World Bank [WBF] and Taiwan's Ministry of Economic Affairs [BoEa]. All data for 2016, except The World Bank's data, for 2015 or 2014

On the other side, the Far Eastern small states are largely exposed to international energy markets. We mentioned that their energy needs are large and, on the contrary, their domestic energy resources are either small or almost non-existent. Consequently, they must import almost all their primary energy: 98% in Taiwan [BoEc], 93% in Japan and 81% in South Korea [WBEa]. These shares are among the largest in the world (Figure 3.12), even with domestic nuclear energy: it *eases*, *not erases* the dependency [GAM<sup>+</sup>17].

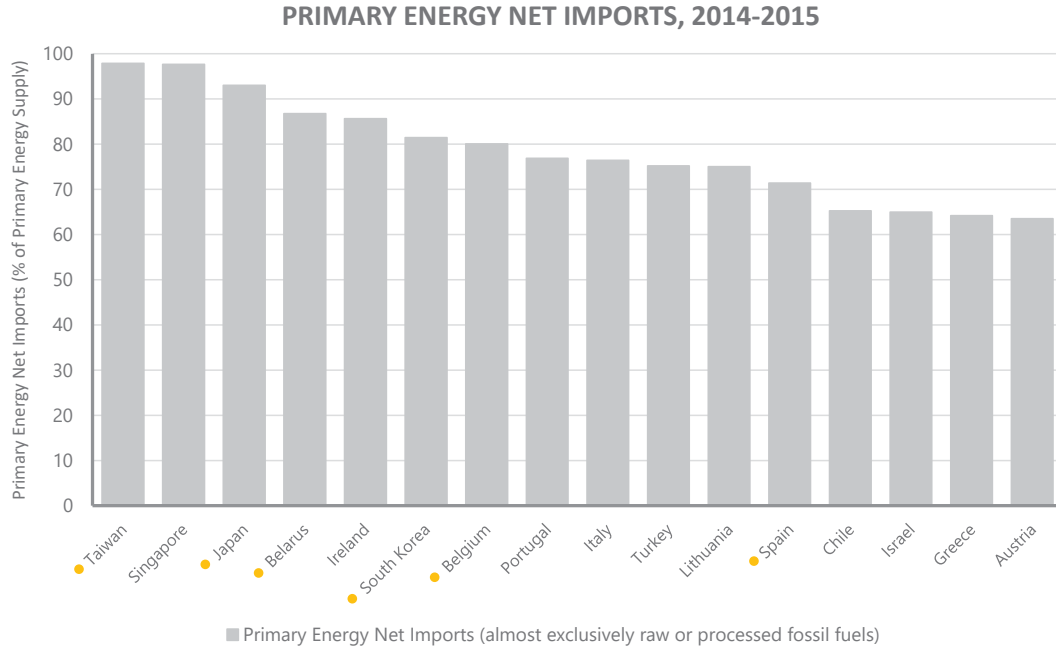
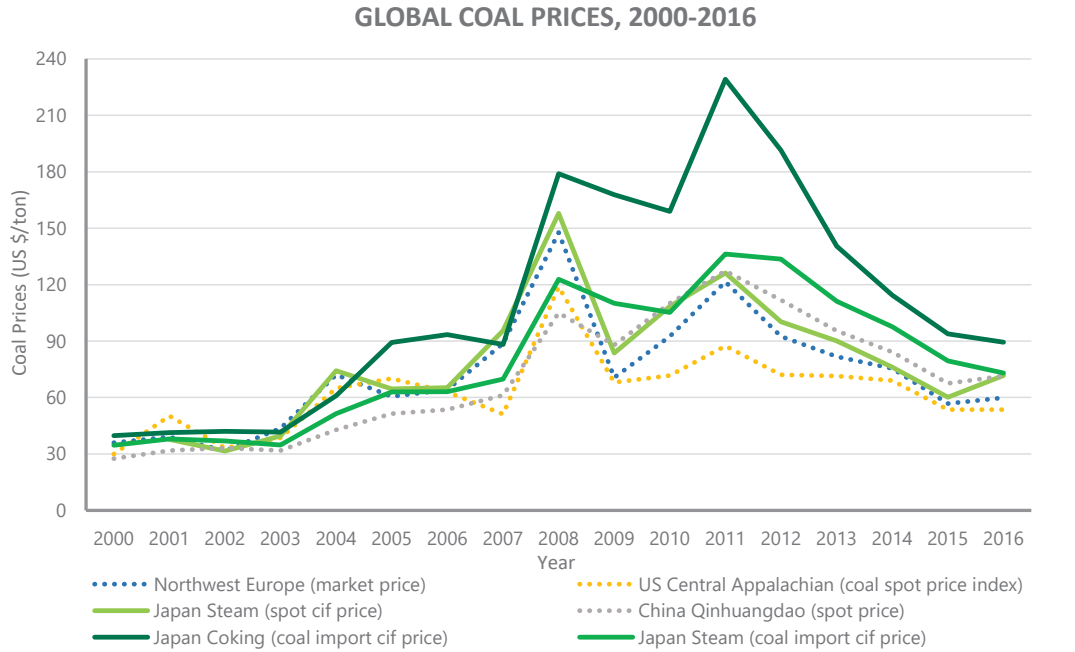
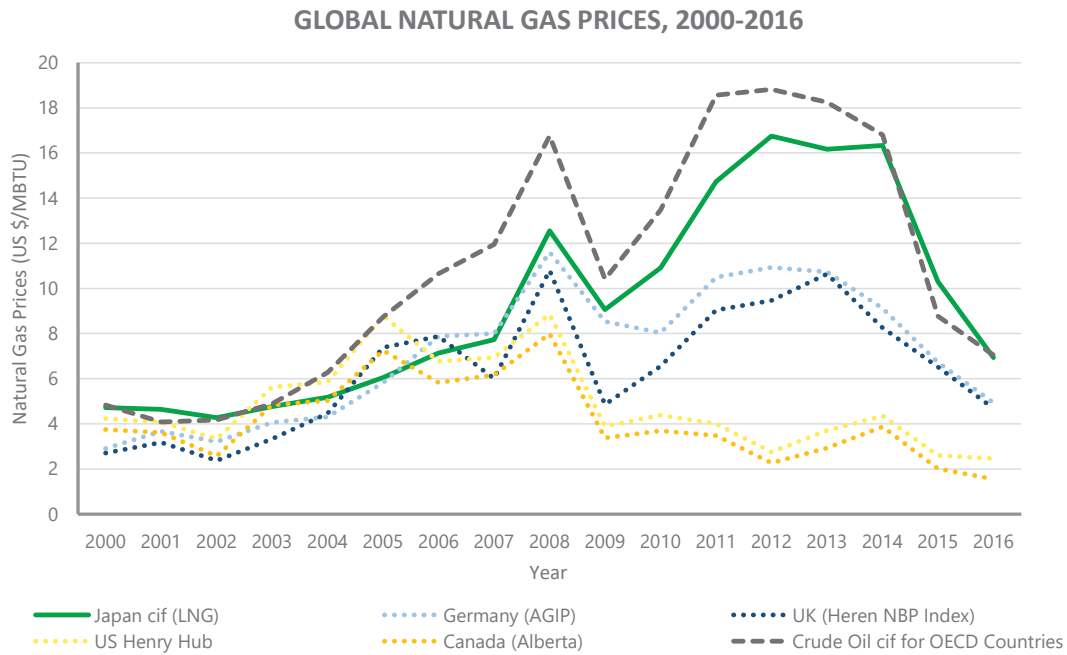


Figure 3.12: Primary energy net imports, expressed as % of primary energy supply. We depict the top quartile of the 66 individual countries in [BPS17]. The extreme quartiles reveal opposing energy trade additions: between 98% and 64% in the top, between -73% and -581% in the bottom. Data from The World Bank [WBEa] and Taiwan’s Ministry of Economic Affairs [BoEc]. Taiwan’s data for 2016, the rest for 2015 and 2014

This is nuclear’s second manifest strength: nuclear fuel trade. On one hand, nuclear fuel generates more electricity per unit mass than fossil fuels, which implies less trading volumes. Take the US in 2015 and 2016: it produced 39.3 electrical MWh/kg of fresh  $U_3O_8$  equivalent [IAE17b] & [EIA17a], which is 3 and 4 orders of magnitude higher than values for natural gas and coal respectively [Admc] & [IGU12]. On the other hand, nuclear fuel trades on a private market (buyers and sellers independently agree prices) that is dominated by long-term pricing [Cora] & [Traa]. Besides, this market is oversupplied, with sustained exploration and decreasing spot prices since the late 2000’s [Traa]. All in all, nuclear fuel is less exposed to market fluctuations than fossil fuels (Figure 3.13).



(a) Natural gas prices, in US \$ per million BTU



(b) Global coal prices, in US \$ per ton

Figure 3.13: Natural gas and coal prices between 2000 and 2016. “cif” stands for Cost + Insurance + Freight. In contrast to crude oil markets, natural gas and coal markets are geographically decoupled, most remarkably right after 2011’s Fukushima. Japanese LNG and coal imports have been the most expensive in the world between 2011 and 2016 (even accounting for the worldwide LNG boom). Actually, Japanese LNG prices matched its crude oil prices on an energy basis between 2014 and 2016. Moreover, the LNG relief might not last: Bloomberg New Energy Finance expects LNG supply shortages in the late 2020’s [BNE17a]. In parallel to Japan’s energy exposure, South Korea’s and Taiwan’s are relatively similar, at least in LNG terms [BoEb]. Data from BP [BPS17]

You may argue that nuclear energy is a double-edged sword in geostrategic terms. Under ordinary conditions, nuclear fuel trade is an *advantage*: less exposure to international energy markets, since it is a private market with long-term pricing schemes. Conversely, under extraordinary conditions (such as Fukushima), nuclear fuel trade reveals itself as a *patch*: if the importing country was vulnerable to energy imports and can no longer count on its nuclear generation, the country becomes even more vulnerable. In Medicine, they would call this phenomenon ***withdrawal effects***: “the development of new symptoms characteristic of abrupt cessation of the medication” [oGHP]. They may appear with the cessation of any energy source, but are most abrupt with the cessation of nuclear generation.

Japan suffered from these withdrawal effects in 2011. Almost all nuclear generation halted after Fukushima [IEAd] (“abrupt cessation of the medication”) and Japanese primary energy imports soared from 80% in 2010 to 89% in 2011 and a stable 93-94% between 2012 and 2015 [WBEa] (“the development of new symptoms characteristic of abrupt cessation of the medication”). The missing nuclear generation was balanced with lower primary energy consumption and higher imports of coal and natural gas [IEAd]. In a time when LNG markets were more fragmented, Japan imported the most expensive LNG in the world between 2011 and 2016, even matching crude oil prices on an energy basis between 2014 and 2016 (Figure 3.13). Since August 2015, Japan is only gradually “taking again the medication” [Traa] and as of November 2017 only 5 of its 42 operable reactors have restarted operation.

On the contrary, Germany did not suffer from these withdrawal effects. 1/4 of German nuclear generation was shut down after Fukushima [IEAc], but its primary energy net imports hardly varied. In fact, they hardly varied between 1996 and 2015, always around 60% [WBEa] despite the renewable boom or the nuclear partial closure. The remaining 3/4 of German nuclear generation will shut down in 2022 [Gera] & [IEAc], which might trigger larger withdrawal effects, if it were not for the large domestic reserves of low-graded coal. Remember, Germany holds the third-largest reserves of low-graded coal (subbituminous and lignite) in the world [BPS17]. If Germany did not care for its GHG emissions, pre-2011’s Germany and post-2022’s Germany would be as exposed to international energy markets. In this case, nuclear generation would offer no geostrategic advantage.

So far we have explained how two manifest strengths match the energy ecosystem of the Far Eastern small states. On one side, as small *islands* with huge energy needs, they have some of the largest electricity densities (Figure 3.11). Thus, they value nuclear’s high energy density. On the other side, with scarce domestic resources, they import almost all its primary energy (Figure 3.12). Thus, they value nuclear fuel trade: a private market with long-term pricing. Could we combine both indicators (“electricity density” and “energy imports”) into one single indicator? Yes, into the density of primary energy net imports (Figure 3.14), if we assume electricity consumption is linearly correlated with primary energy consumption.

## NATIONAL PRIMARY ENERGY NET IMPORTS DENSITY, 2016

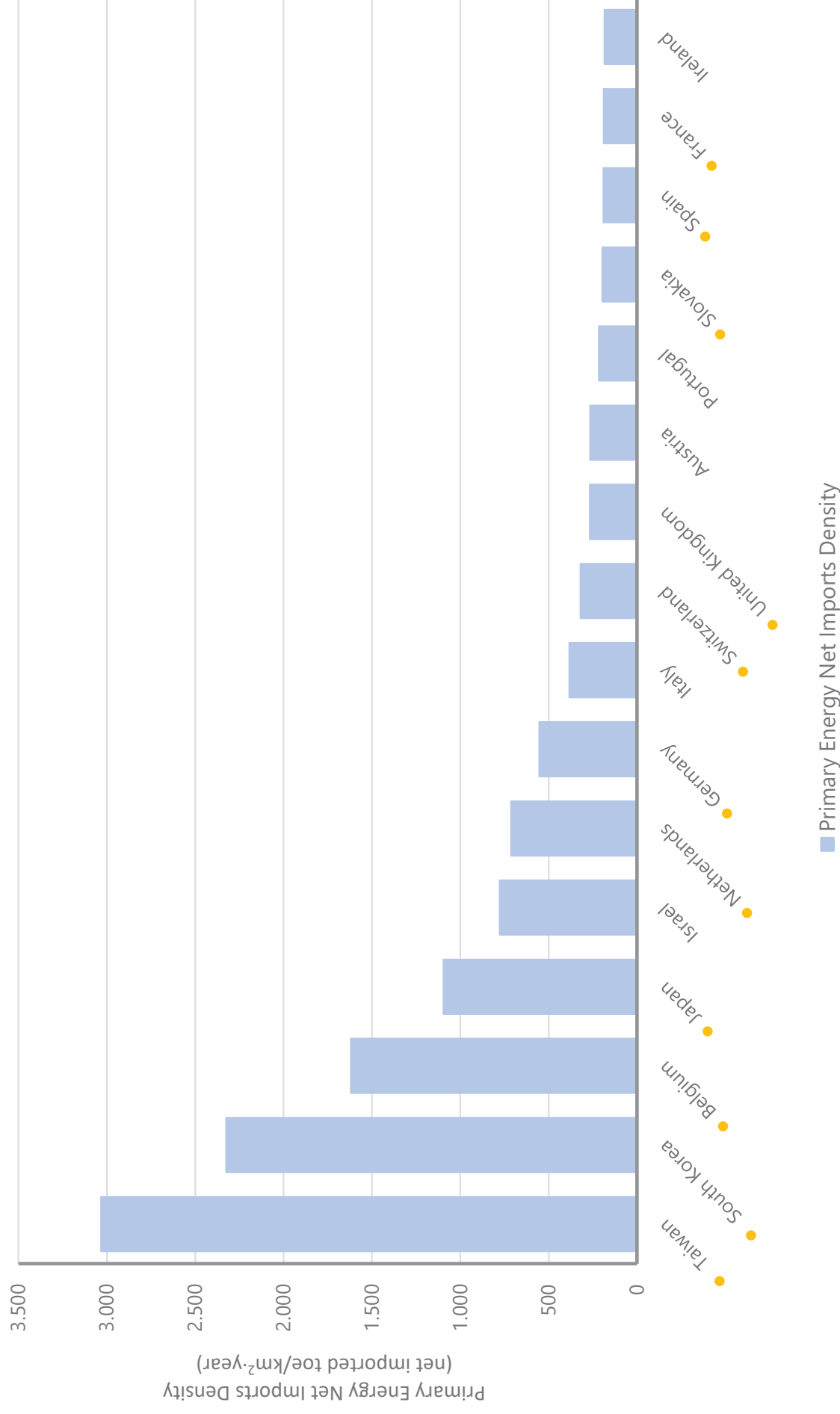


Figure 3.14: Density of primary energy net imports, in yearly tons of oil equivalent per km<sup>2</sup> of surface. We computed it for 2016 for the 66 individual countries in [BPS17] (90% of worldwide primary energy) and we depict it for the top quartile. 11 out of the 31 nuclear countries in [BPS17] are in the top quartile. Singapore ranks first, with 114200 net imported toe/km<sup>2</sup>·year, not represented to prevent scale overflow. Primary energy supply data from BP [BPS17], surface data from The World Bank [WBS] and Encyclopedia Britannica [KWC], primary energy imports from The World Bank [WBEa] and Taiwan's Ministry of Economic Affairs [BoEc]. All data for 2016, except The World Bank's data, for 2015 or 2014

Furthermore, the South Korean energy ecosystem *may* value a third manifest strength: the *diminishing overnight construction costs* (OCC) of South Korean nuclear development. Its learning curves for nuclear OCC are indeed exemplary [LYN16]: no small-scale development phase, an early phase of 9 imported large-scale reactors and a later phase of 16 domestic reactors, showing a long-term trend of diminishing OCC. Alas, OCC are incomplete financial measures, since they exclude capital costs and cost overruns, which are inherent to multi-year-construction infrastructure projects [KHG16] & [GSJS16]. Therefore, OCC trends are inaccurate indicators for overall nuclear costs and, accordingly, the South Korean energy ecosystem *may* or *may not* value these trends.

How did these OCC trends actually evolve? During the early phase, 9 imported reactors began construction between 1972 and 1993 and their OCC diminished by 25% in that period. During the later phase, 16 domestic reactors began construction between 1989 and 2008 (slightly overlapping the early phase) and their OCC diminished by 13% in that period. The OCC of the very last reactors achieved OCC between 1700 and 2200 \$ per kW (expressed in 2010 USD [OFX]), comparable to the OCC of the last US reactors completed before 1979’s Three Mile Island [LYN16].

In particular, the very last reactor (Shin-Kori 3 [Ageb]) is the first of a novel South Korean design, the domestic APR1400 [222]. One APR1400 is already operational and eight more are under construction in the East: 4 in South Korea [Ageb] and 4 in the UAE [Car17]. If this new technology proves cost efficient in terms of OCC *and* capital costs, South Korea could further export these novel reactors. As a side benefit, the South Korean energy ecosystem would value nuclear energy for another face of geostrategy: boosting technology knowledge and exports. South Korea, as the 7<sup>th</sup> largest exporter in the world [oECO], would surely appreciate it.

Despite these 2 or maybe 3 manifest strengths, the Far Eastern small states (especially South Korea and Japan) are suffering from one acute, manifest weakness: **safety**. Speaking about safety in the Far East, the first word that comes to mind is “*Fukushima*”. Now, pause for a moment and tell yourself Fukushima’s story. Maybe you forgot to mention the triggering earthquake and tsunami or the post-disaster health conditions, which caused nearly 20000 deaths [Edi17a] & [NI13], but you did not forget to mention the nuclear accident... Shall I only ask you for the name of the triggering earthquake? It has two names, “Tohoku” or “Sendai” [PR]. The Fukushima accident was *one* of its consequences.

Focusing just on the nuclear accident, Fukushima health impacts may be lower than in public imagination. The World Health Organisation (WHO) preliminary estimated in 2013 that radiation health risks would be unnoticeable outside Japan, although the lifetime risks for some cancers may increase above baseline rates in the most affected areas of the Fukushima prefecture [WHO13]. Among these lifetime risks, WHO pointed mainly to increased rates of thyroid cancer in (female) infants

[WHO13]. Fortunately, early-caught thyroid cancer is almost always cured by removing the thyroid gland and, consequently, Japanese authorities are conducting extensive thyroid screening among the Fukushima population to detect early any possible thyroid cancers. However, health impacts are disputed and the international medical community is divided over the medical response [Nor16].

Beyond health impacts, economic ones are astonishing: current estimates of Fukushima disaster-related costs amount to \$188 billion [OH16]. Let's put this figure into context: it is 25% higher than all credit-crisis fines in the US between the burst of the financial crisis (2008) and nowadays (last updated in August 2017) [Sca17].

Leaving aside Fukushima, there is a second safety issue: **“North Korea”**. North Korea is located in the middle of the Far East (Figure 3.15) and its recent history combines hostility and reconciliation over the last 6 decades. From wartime experiences (WWII, the Korean War or the remaining Cold War) to peacetime approaches to the United Nations (both Koreas were admitted simultaneously in 1991), the US (failed non-proliferation agreement) or the six-party talks among China, the US, both Koreas, Japan and Russia (early 2000's) [oEBb] & [Yin17].

Every progress made was always shortly derailed [Yin17]. Main expressions of this derailment are the North Korean nuclear and ballistic missile programmes, that have accelerated lately. While Kim Jong-Il conducted 16 missile tests and 2 nuclear tests between 1994 and 2011, Kim Jong-Un has conducted 86 missile tests and 4 nuclear tests between 2011 and 2017 (as of November 29, 2017) [HL17a].

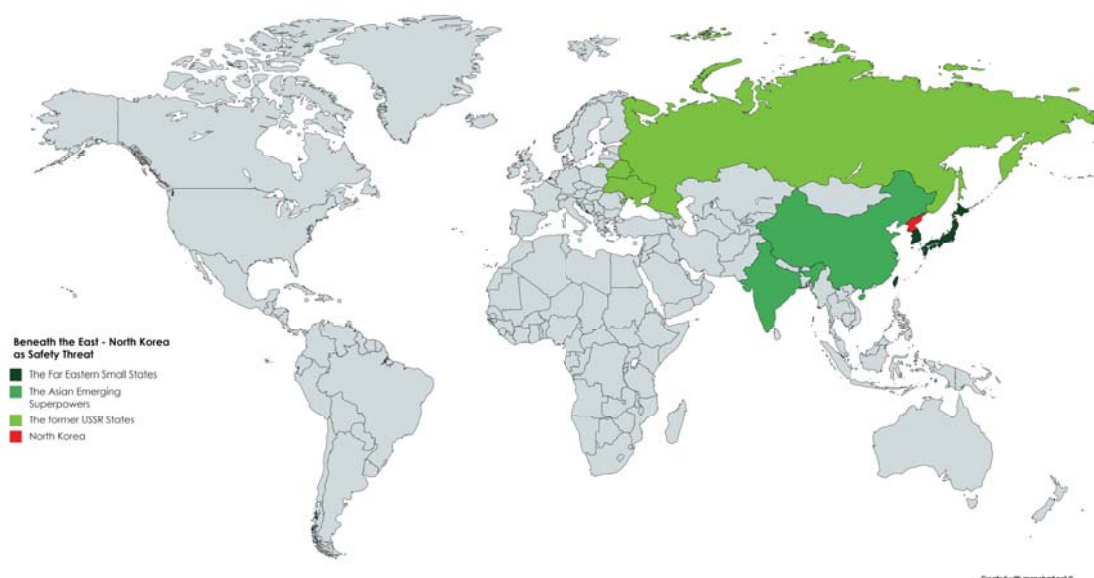


Figure 3.15: North Korea threatens the safety of the Far East and beyond. Map created with MapChart [Map]



Under Kim Jong-Un, North Korea has ramped up the *number* as well as the *magnitude* of its tests. Nuclear tests have been escalating in yield: experts estimated that the latest nuclear test (September 2017) surpassed the 140 kilotons of yield [fSP], which is more than 9 times that of Hiroshima nuclear attack [HL17a]. Meanwhile, the ballistic missiles able to carry those nuclear heads have grown in range. The most advanced Hwansong-15, first launched at the end of November 2017, claims to have the entire US territory within range [HW17]. After this launch, Kim Jong-Un reportedly stated “*with pride that now we have finally realised the great historic cause of completing the state nuclear force*” [HW17].

The national sanctions against North Korean provocations have come mainly from the US and China. Take first the US and Trump’s warning of “*fire and fury*” to combat its nuclear threat [Rac17]. At the end of 2017, US authorities relisted North Korea as “state sponsor of terrorism”, urging more countries to suspend trade with the rogue state [Sev17]. In parallel, US sanctions have targeted North Korean trade in Chinese territory (which currently accounts for 9/10 of all North Korean trade), placing sanctions on a Chinese bank (Bank of Dandong) and threatening other Chinese banks if China did not reduce ties with North Korea [Wei17] & [SM17].

China has indeed responded, either to US sanctions or to the perspectives of a neighbouring nuclear conflict (in that event, China would be literally on the frontline, exposed to nuclear fallout and refugee flows [Rac17]). In particular, Chinese banks have banned North Koreans from opening new accounts [YL17] and the Chinese Ministry of Commerce has ordered all North Korean businesses in Chinese territory to close before February 2018 [CHL17]. Unsurprisingly, Chinese experts have manifold and conflicting views about the best way forward [Rac17].

How would North Korea respond? Nobody knows. In the words of Nikki Haley, US’ ambassador to the UN: “*They’re getting ready to feel 90 per cent of their exports going away, 30 per cent of their oil [...] there is no way that North Korea doesn’t feel this; how they choose to respond to this is totally in their hands*” [HJAS<sup>+</sup>17].

This unpredictable, deepening crisis around North Korea concerns two of our Far Eastern small states: South Korea and Japan. Moon Jae-In, South Korea’s president, dismissed dialogue among the two Koreas as a possible solution [HJAS<sup>+</sup>17] and urged a “*complete defence reform at the level of a rebirth instead of making some improvements or modifications*” [HL17b]. The same Moon Jae-In had announced the phase out of South Korean nuclear generation months before. Chances are the underlying reasons could be *partially* shared: it is treacherous to build and operate nuclear reactors when your closest neighbour would not hesitate to target them with ballistic missiles and nuclear weapons.

Recently, South Korea resumed two reactors in suspended construction, but will cancel plans for 6 new reactors and will not allow life extensions for the operating

ones [JA17b]. As a consequence, South Korea will expand its nuclear generation in the coming years (4 reactors under construction [Ageb]), but it will diminish from then on (10 of its operational reactors are expected to shut down no later than 2038 [JA17b]). South Korea cannot contribute to an ambitious expansion of nuclear energy (at least with its domestic generation) and even less with the threat of North Korea right next door.

Two flight hours to the East, Japan lies under explicit threat: *“The four islands of the [Japanese] archipelago should be sunken into the sea by the nuclear bomb of Juche [North Korea’s official ideology] [...] Japan is no longer needed to exist near us”* [Har17b]. Matching words with deeds, North Korea fired two ballistic missiles that flew past Japan in August and September 2017. Although Japan has more time for reaction than South Korea and already has missile-intercepting destroyers at sea, it is planning to reinforce its onshore missile defence with Aegis Ashore systems [Har17a] & [Mar].

In this unsafe context (threatened by North Korea, ailing from Fukushima), nuclear generation in Japan may be gradually restarting operation, but will take time to approach pre-Fukushima values [Assd] and will find it harder to spread beyond pre-Fukushima values. Japan: recover, yes; further expand, not yet.

At last, Taiwan’s nuclear generation may concern less about overseas North Korean threats and concern more about domestic policy-makers and civil society stakeholders. The situation is dire for nuclear generation in Taiwan: the majority of Taiwanese oppose nuclear energy after Fukushima, which adds up to the fact that the founding charter of the ruling Democratic Progressive Party also opposes it [Eco17d]. A new reactor that completed construction in 2014 has never started up. Tsai Ing-wen, new Taiwan’s president, promised to phase out nuclear generation in 2025 [Eco17d]. Nuclear generation will struggle to survive in Taiwan.

In essence, **the national balances of the Far Eastern small states are against nuclear energy**. They match 2 or maybe 3 manifest strengths (high energy density & stable fuel trade, maybe diminishing OCC) and mismatch 1 very acute manifest weakness (safety after Fukushima, safety in relation to North Korea). Taiwan will not further expand nuclear generation and will phase it out in 2025. The same applies for South Korea, but with an initial modest expansion (5.4 GW [Ageg]) and a more gradual decline, with a complete phase out in 2060. Japan will gradually recover pre-Fukushima values, but will delay a potential expansion.

Nuclear energy has been migrating from the West towards the East, but will not likely migrate towards the Far Eastern small states in the next years. Where will nuclear generation migrate then?

### 3.4.2 The Asian emerging superpowers

China and India are huge countries with huge populations and emerging economies. Altogether, they have 2.9 times the surface of the European Union, 5.3 times its population and only 0.8 its GDP [WBS] & [WBP] & [Bana]. Their financial boom is still unfolding: China and India were low-income economies in the 1980's, but experienced a trade boom in the last decades (their exports grew tenfold between 1995 and 2016 [oECOb] & [oECOe]) to become middle-income economies [Banc].

Along their financial emergence, *air pollution* emerged too. Within the major air pollutants, fine particulate matter (“fine” meaning less than  $2.5\ \mu\text{m}$  of diameter) is the most hazardous to human health [IEA16c]. It is alarmingly common in some Asian countries (Figure 3.16) and is seriously hazardous: fine particulate matter (PM2.5) is the worldwide leading *environmental* risk factor for premature death and ranks 5<sup>th</sup> among *all* risks factors, behind high blood pressure, smoking and diet [Sta17a]. It is responsible for cardiovascular and chronic respiratory diseases, lower-respiratory infections and cancer [Sta17a].

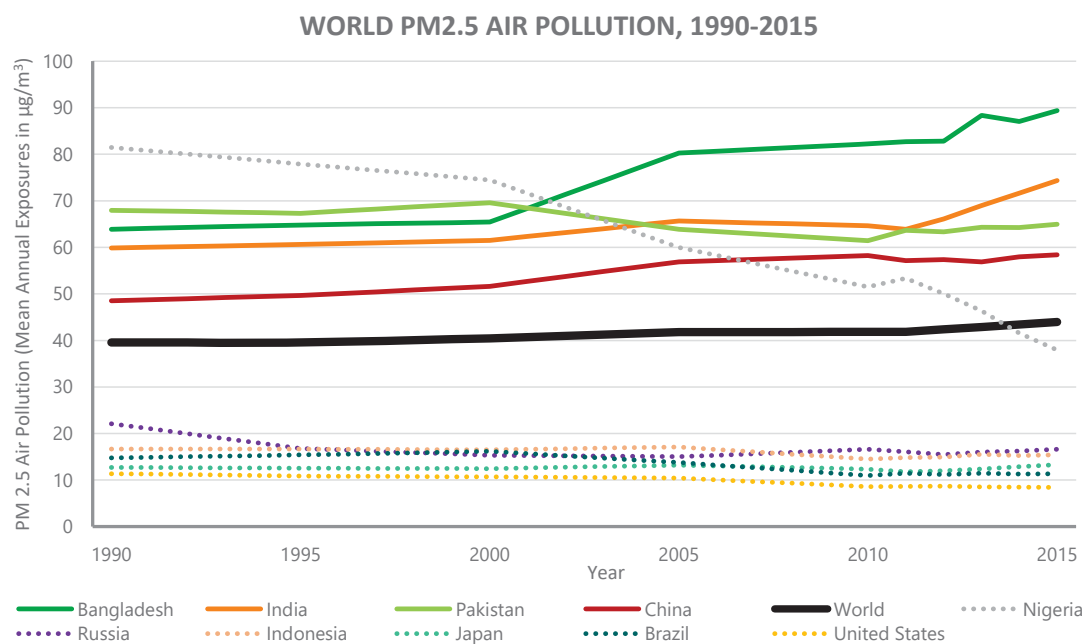
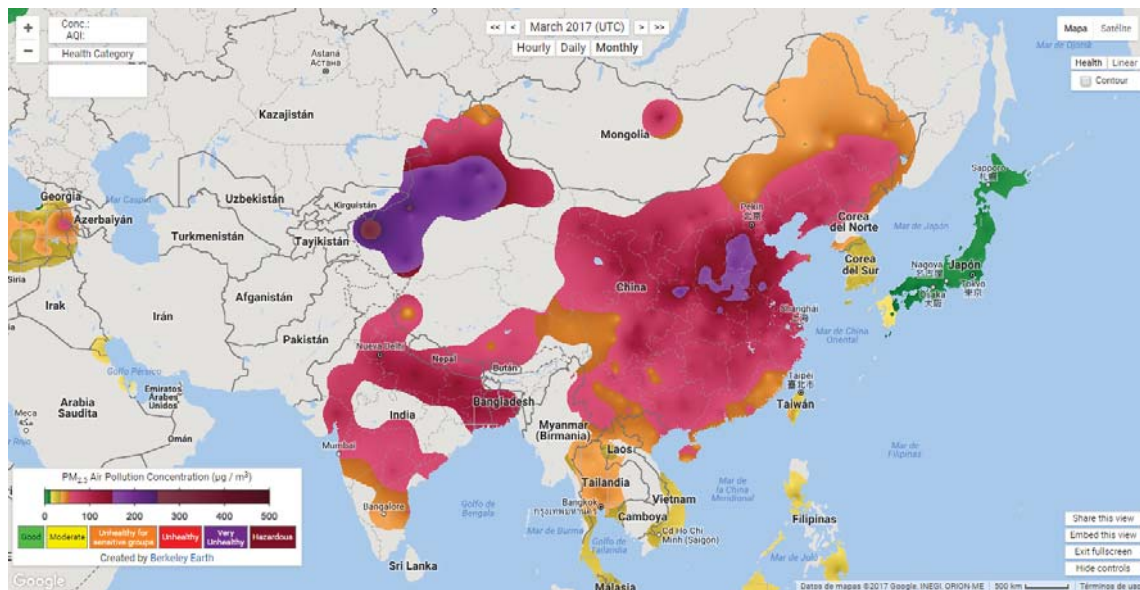
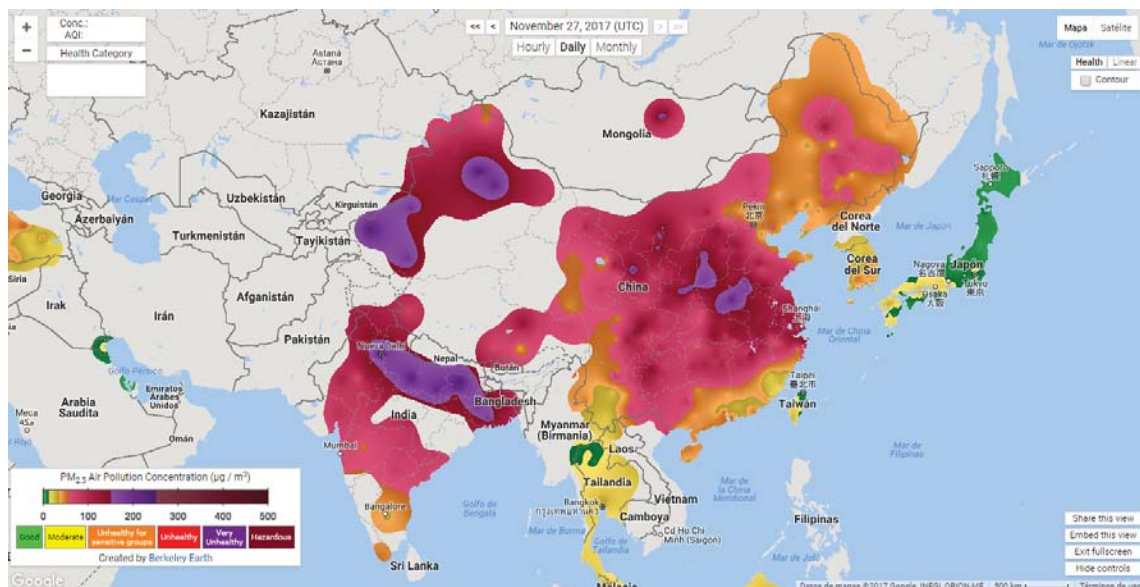


Figure 3.16: Population-weighted exposures to ambient PM2.5 (average of *local* PM2.5 exposures weighted by corresponding *local* populations [ea17a]), expressed in  $\mu\text{g}/\text{m}^3$ . We depict this indicator for the ten largest populations in the world (as of 2015). If a country is always above the world average, it is depicted as solid line (otherwise, as dotted line). Bangladesh, India, Pakistan and China consistently score the worst. Data from The World Bank (5-year averages from 1990 until 2010, 1-year averages from 2010 until 2015) [WBAb]

Worldwide ambient PM2.5 is severely hazardous: it caused 4.2 million deaths in 2015 (95% confidence interval: [3.7, 4.8] million deaths) [ea17a]. Let's put this figure into context: it caused more deaths than AIDS, tuberculosis and malaria combined and approximately 7 times more than all wars and other forms of violence [ea17c]. Eastern and Southern Asia suffer the most from ambient PM2.5 (Figure 3.17): 3/5 of its worldwide deaths are concentrated in this area [ea17a] and, besides, nearly 9/10 of PM2.5 most extreme exposures (above  $75 \mu\text{g}/\text{m}^3$ ) were registered in 4 of their countries (in China, India, Pakistan and Bangladesh) [Sta17a].



(a) Ambient PM2.5 Concentration, March 2017 Average in  $\mu\text{g}/\text{m}^3$



(b) Ambient PM2.5 Concentration, 27<sup>th</sup> November 2017 Average in  $\mu\text{g}/\text{m}^3$

Figure 3.17: Ambient PM2.5 concentration in China and India. The worst affected regions in China are the Western province of Xinjiang and the Eastern triangle among Beijing, Shanghai and Xi'an; in India, the corridor between New Delhi and Kolkata. Most recent monthly and daily data from Berkeley Earth (as of 28<sup>th</sup> November 2017) [Ear]

How can we alleviate air pollution? Some causes of air pollution are beyond our control, such as dust storms, particularly in regions close to deserts [WHO]. However, the main cause of air pollution is indeed within our reach: the combustion of fossil fuels and biomass, responsible for between 85% and almost all sulfur oxides, nitrogen oxides and particulate matter that reach the atmosphere [IEA16c].

If we focus on PM2.5, the most hazardous to human health, we can draw on previous US experience to find potential solutions: aggressive air quality measures, focusing on coal combustion, household burning of fossil fuels -and biomass burning, never forget- and road transport [ea17a]. Since nuclear energy is a “natural” substitute for coal combustion for electricity generation, the energy ecosystem of the Asian emerging superpowers matches with one nuclear internal strength: **low human-health impact** (low air pollution). The IAEA shares this vision: acute local pollution will (at least partially) drive nuclear expansion in China and India [IAE16] (actually, Pakistan and Bangladesh, suffering harshly from air pollution, are also expanding their nuclear fleets [Ageg]).

Let’s start with India. Smog is blanketing much of northern India [Edi17b]. Recently, in November 2017, the PM2.5 levels in New Delhi reached almost 30 times the WHO safety standards: 4000 schools closed for nearly a week, the Indian Medical Association called this smog a “*public health emergency*” and New Delhi’s chief minister called the city “*a gas chamber*” [SKG17] & [Kaz17]. Indian authorities cannot overlook what New Delhi’s emergency evidences: air pollution is a very serious issue in India and every cleaning measure must be seriously considered.

If we combine this first cleaning imperative with a second accessibility imperative (still 1 every 5 Indians lacks access to electricity [WBAa]), nuclear generation in India still has a role to play. In this line, the Indian government is indeed promoting its nuclear expansion [Sta17b].

Currently, India’s nuclear fleet is transitioning towards larger reactors: from small-sized reactors (22 reactors in operation, averaging less than 0.3 GWe per reactor [IAE17b]) towards medium-sized (7 reactors under construction, averaging around 0.65 GWe [IAE17b]). Chances are the transition to larger reactors will continue. Most recently, the last Indian reactor starting construction will be the first large-sized reactor in India, with more than 0.9 GWe [Aged]. In the coming years, more and larger reactors will likely start construction: 3 according to IAEA’s records [IAE17b] (1 large-sized, 2 middle-sized), 11 if we combine IAEA’s records and declarations of the Government of India [oAEI] (probably 1 large-sized, 10 middle-sized). Nuclear generation will successfully migrate towards India.

Let’s continue with China, where smog is also problematic [But17a]. Xi Jinping, China’s president, has promised a dramatic improvement of air quality by means of an energy revolution “*to make the skies blue again*” [But17a] and results

are already visible [Hor18]. China is cleaning the consumption points (at least 40% of EVs on the worldwide roads by the end of 2017 will be in China [But17a]) as well as the generation points. As for the generation, China will transition from the dominance of coal (China consumes more coal than the rest of the world [But17a]) towards renewable energy (leads the renewable infrastructure supply [PR17] and the renewable electricity consumption [IEA17b]) and towards nuclear energy.

The Chinese nuclear expansion is exemplary. Even though it is only a new-comer, China is already the largest nuclear-generating country in the East (albeit still behind Japanese pre-Fukushima values) and the third largest nuclear-generating country in the world (behind the US and France) [IAE17b].

How does this exemplary nuclear expansion fit into the nuclear migration from the West towards the East? Let's now dig deeper into the migrating trend by segmenting the Figure 3.4 according to **Western, Eastern and Chinese contributions**. Figure 3.18 shows the *absolute* regional contributions (in GWe), whereas Figure 3.19 shows the *relative* regional contributions (in % of yearly global contributions). Notice that Figure 3.19 starts in 1963 to avoid nervous oscillations due to minimal changes in the very first years of nuclear development.

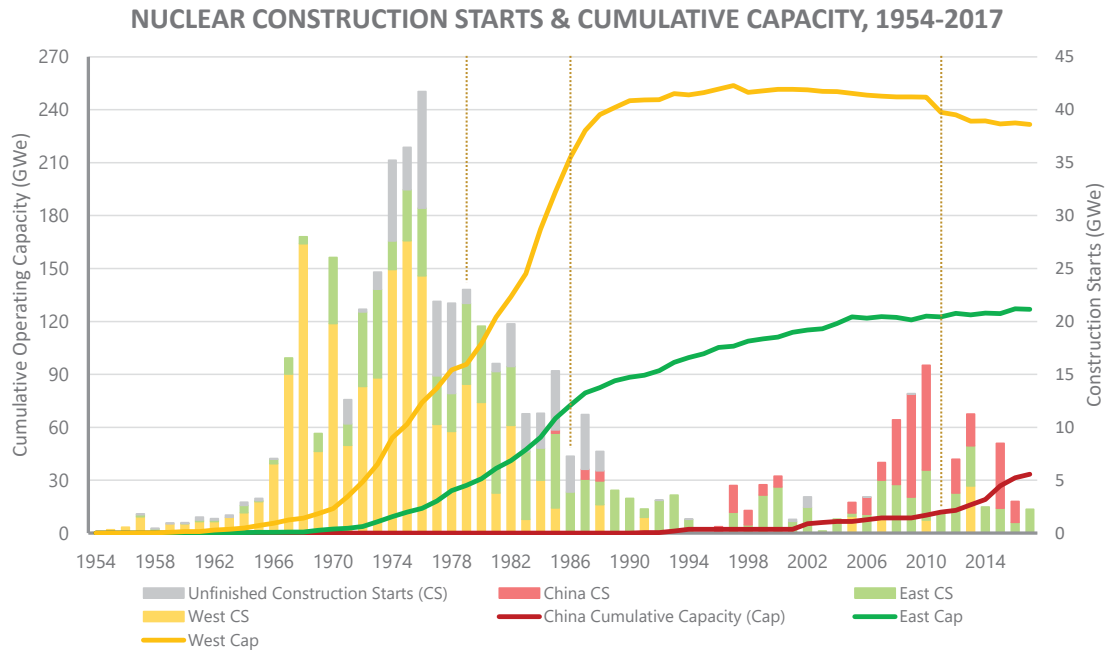
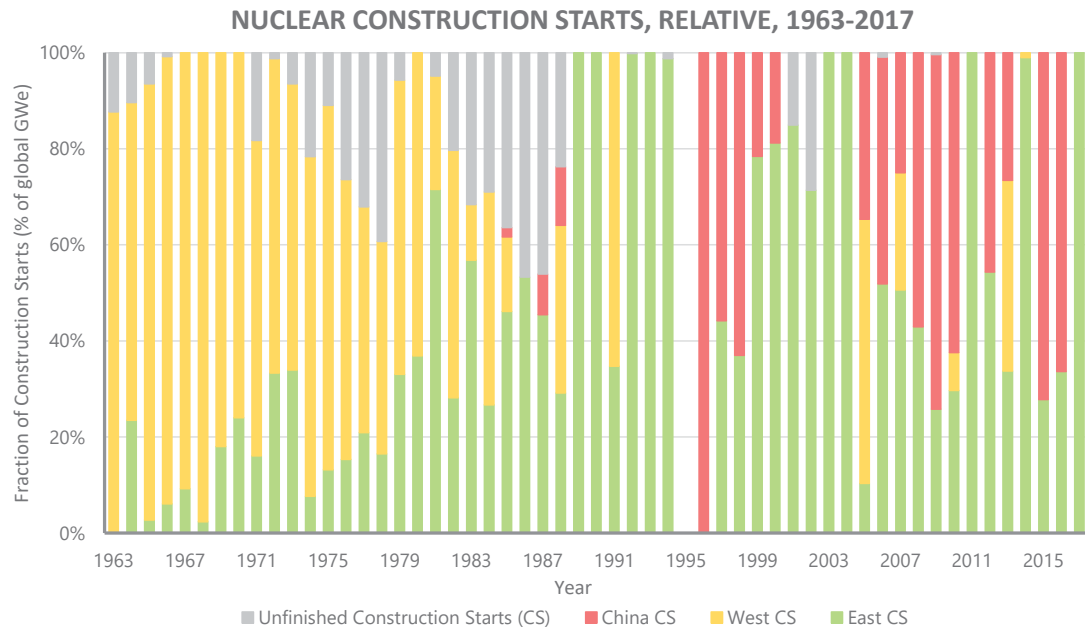
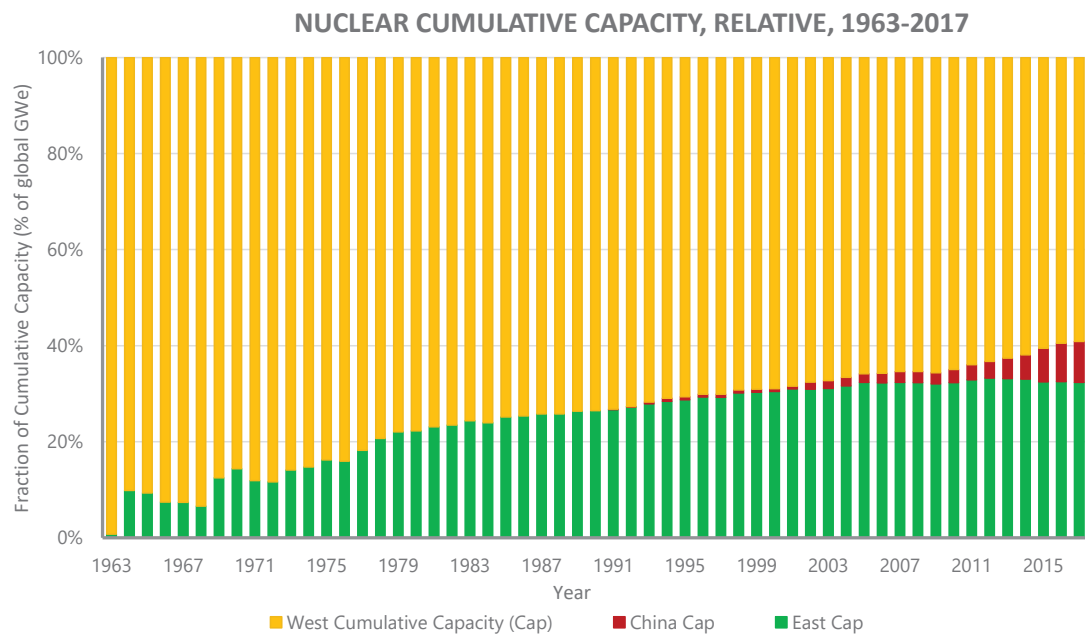


Figure 3.18: Nuclear cumulative operating capacity and construction starts, expressed in net electrical GWe and segmenting according to Western, Eastern (without China) and Chinese contributions. Unfinished construction starts embrace all projects that started construction but were cancelled before completion. The recent suspensions of Summer-2 and Summer-3 in the US are not yet included in this category, since they could still restart [War17]. Data from IAEA [IAE17b] & [Aged]



(a) Nuclear construction starts per region, in % of global GWe starting construction each year



(b) Nuclear cumulative capacity per region, in % of global GWe of cumulative capacity each year

Figure 3.19: Nuclear construction starts and cumulative capacity respectively. The West dominated construction starts until the late 1970's, when the nuclear accidents in Three Mile Island and Fukushima struck the US and Europe. The East *as a whole* has dominated construction starts since the late 1980's and China *in particular* since the mid 2000's. The all-through consistency of the East *as a whole* is reflected in its steadily increasing share of worldwide cumulative capacity, exceeding today 40% of the worldwide total. Data from IAEA [IAE17b] & [Aged]

Nuclear energy has been migrating from the West towards the East *as a whole* since the late 1980's and towards China *in particular* since the mid 2000's.

The West dominated construction until the late 1970's, until Three Mile Island and Chernobyl turned the tables around. Between 1979 and 1993, Western construction vanished and 53 of its reactors under construction were cancelled (38 of them in the US), whereas only 14 reactors under construction were cancelled in the East (almost exclusively in Central and Eastern Europe). Consequently, Western cumulative capacity hit a plateau in the early 1990's. Shortly before, the West had passed the baton of construction starts to the East *as a whole* in the late 1980's, which passed it to China *in particular* in the mid 2000's. Chinese growth has driven Eastern growth during the last decade, even after Fukushima (only 4 reactors under construction were cancelled, exclusively in Central and Eastern Europe).

The recent awakening of China influences the distribution of reactor ***operational lives***, as depicted in Figure 3.20 segmenting by status (shut down or operational) and region (West, East or China, but only for the operational reactors). Western reactors concentrate in the older year clusters (mainly between 28 and 47 years), Eastern reactors outside China are quite homogeneously distributed across all ages and Chinese reactors concentrate in the younger year clusters (mainly between 0 and 15 years). *“Living” reactors are younger in the East, especially in China.*

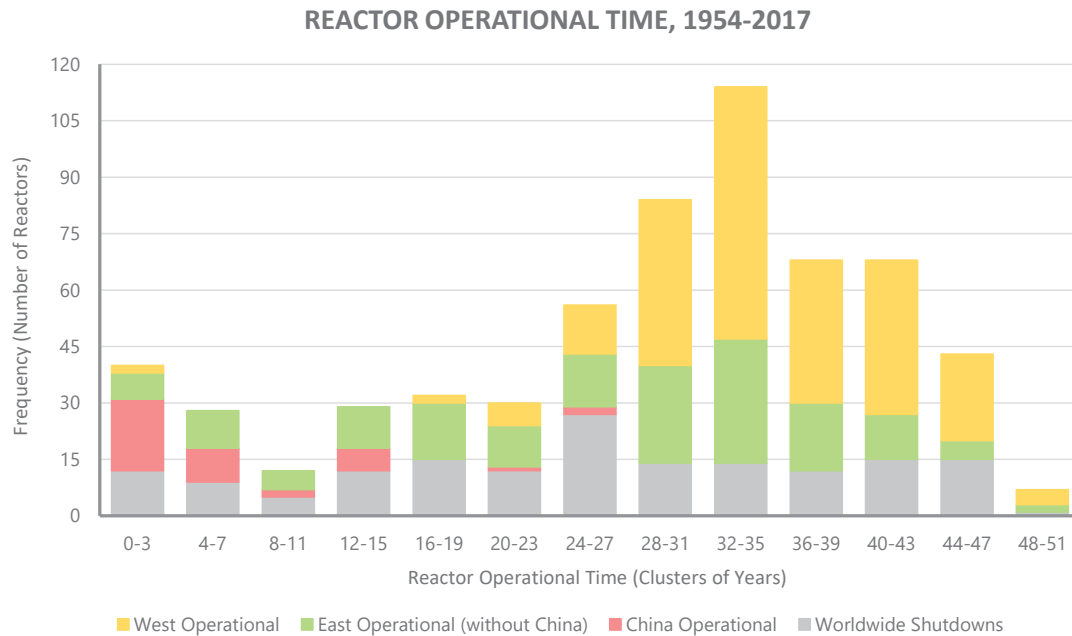


Figure 3.20: Nuclear reactor operational time, in years since the first connection to the grid until its shutdown (for shut down ones) or until December 2017 (for operational reactors). Operational times are fairly aged in the West, fairly homogeneous in the East, fairly young in China. Data from IAEA [IAE17b] & [Aged]



Besides, China has improved its *normalised construction times* over the years (Figure 3.21). Nuclear construction in China started in 1985, 3 decades later than the early movers. Soon, China reached Eastern NCTs as international contractors (from Russia, France and Canada) cooperated with domestic ones. Nowadays, the latter are leading: they have connected to the grid the last 25 GWe, with NCTs of 5.6 years [IAE17b] & [Aged]. Since the profitability of nuclear reactors is highly influenced by construction duration [CTBK16], Chinese construction consistency and agility mean higher profitability. Therefore, the Chinese energy ecosystem matches with a second nuclear internal strength: **higher nuclear profitability**.

Let's delve into one international contractor, AREVA, because it has two different faces inside and outside China. AREVA is building 4 EPRs: 2 in the West and 2 in China [New17]. None has finished construction as of December 2017. The Western ones were the first to start construction, are years delayed and billions over budget and will likely start operation between 2018 and 2019 [War17h] & [Mil17]. Conversely, the Eastern ones were the latest to start construction, are months delayed and will likely start operation before mid 2018 [New17]. If these completion dates come true, the 2 EPRs in China will have NCTs of  $\approx 5$  years, compared to  $\approx 7-9$  years for EPRs in the West and 5.6 years for the Chinese domestic contractors.

How do we explain AREVA's NCT trend? We cannot easily isolate its drivers, because manifold variables change from one EPR to the next. A first possible driver is the *order of construction*, "learning by doing", because expected NCTs have decreased as more EPRs had started construction:  $\approx 9$  years for Finland (1<sup>st</sup> EPR),  $\approx 7$  years for France (2<sup>nd</sup> EPR) and  $\approx 5$  years for China (3<sup>rd</sup> and 4<sup>th</sup> EPRs).

A second possible driver is the *supply scope*, in particular the Civil Engineering contractor: the French "Bouygues Construction" is responsible for the EPRs in Finland and France [Conb], whereas Chinese construction companies together with CNPEC are responsible for the EPRs in China [Corb]. Historically, Civil Engineering has been a source of delays and cost overruns in the US, the UK, France, Japan and India: on average, 3 years of delay and 117% of cost escalation per reactor [SGN14]. Recently, Civil Engineering may explain the setbacks in the UK and France: "*In reality, the problem [...] is not caused by any failure of nuclear engineering. The problem is the inability to manage complex projects*" [But17b].

We are inclined to think that China is the opposite story. We trust the "Swiss precision" of Chinese NCTs since 2005. We share the vision of Zheng Mingguang, senior vice president of SNPTC: "*We have a well-established, complete system in place. Not only from the point of view of design, but also manufacturing, quality assurance, safety, construction, and so on. This is why nuclear power in China is economically feasible*" [Gil]. The 2 EPRs in China benefit from this system: they are seizing Chinese nuclear Civil Engineering (not the French one, as its Western counterparts) and will be built swiftly.

## NORMALISED CONSTRUCTION TIME & CONNECTED CONSTRUCTION STARTS, 1963-2013

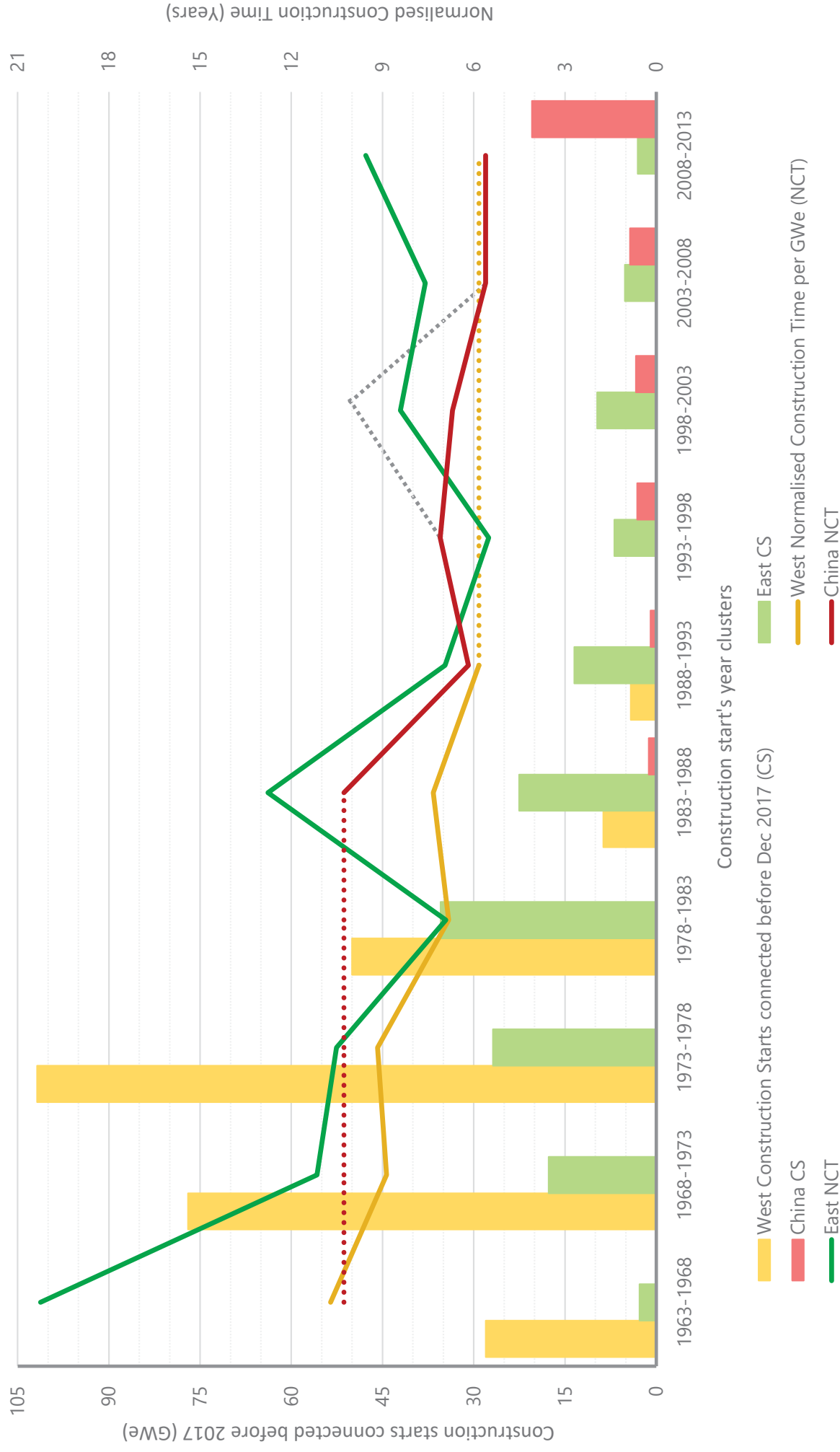


Figure 3.21: “Connected” construction starts (started *during* each year cluster, connected to the grid *anytime* before December 2017), expressed in GWe, and normalised construction times (actual construction times for the “connected” construction starts adjusted for a net electrical power of 1 GWe), expressed in years. Operational and shut down reactors are considered. Changing the clustering patterns typically yields same conclusions: the West has scaled faster in historical terms, the East *temporarily* reached those scalability values in the mid 1990’s and China *consistently* since the mid 2000’s. The grey dotted line in Chinese NCT in the early 2000’s considers the construction of the CEFR, the Chinese Experimental Fast Reactor (0.02 GWe, 11 years in actual construction), whereas the red continuous line does not consider it. Data from IAEA [IAE17b] & [Aged]

So far we have looked inside Chinese borders: 1/3 of the worldwide under-construction capacity, with the unsurprising dominance of domestic designs and the surprising performance of France’s EPR. Now let’s look beyond Chinese borders: Chinese nuclear companies are willing to export Chinese domestic designs worldwide [But17a]. We already mentioned that Chinese companies are building reactors in Pakistan and Romania, are scheduled to build reactors in Argentina, the UK and Iran, are bidding for further projects in Turkey, South Africa and Saudi Arabia and are discussing preliminary deals in Kenya, Egypt, Sudan and Armenia [Cot17a].

As major energy projects, Chinese nuclear exports are inscribed in China’s “*One Belt, One Road*” (OBOR) gargantuan initiative to foster trade by fostering road, rail and energy projects [FKCB16]. When we mean gargantuan, we really mean GARGANTUAN: China has pledged more money *solely* on high-speed rail schemes around the world than *all* the money that went into the postwar Marshall Plan even after adjusting for inflation [Cot17b] & [Sop14]. This is the kind of international leadership, Chinese leadership, that we may be heading for [Eco17e] and the reason why the Chinese energy ecosystem matches with a third nuclear internal strength: **geostrategy** (boosting technology knowledge and exports).

Although nuclear exports are a minor share of the OBOR initiative, precisely 8 of the 12 aforementioned countries are included in the OBOR initiative [oBP]. In particular in Pakistan and Romania, the 2 foreign countries where China is currently building reactors, Chinese banks are also providing nuclear finance: Export-Import Bank of China provides 82% of the investment in Pakistan’s new reactors and *presumably* is contributing with the Industrial and Commercial Bank of China to finance Romania’s new reactors [Cot17b].

China is rising in a shifting international market. Some nuclear providers are undergoing financial trouble, such as AREVA [War17f] & [Eco16] and Westinghouse-Toshiba [CI17] & [War17e]. Some others are undergoing political trouble, such as KEPCO, who may lack governmental support [Cot17b]: “*It is very unusual for nuclear plants to be sold without some government-to-government support. If you have an anti-nuclear government who says, ‘No, we are not gonna develop more nuclear plants’, countries like the UK that potentially want to work with [South] Korea could become a little nervous*” [JA17a]. Some other providers are shifting focus, such as ROSATOM, who will reportedly refocus on hydropower and wind energy (Vyacheslav Pershukov, from ROSATOM’s Management Board, reportedly suggested that the nuclear export market had been exhausted) [Cot17b] & [Foy17].

If we combine all these shifts with China’s exemplary domestic performance and leading technology (2 domestic Generation III+ designs are currently under construction [Assa]), China’s collection of domestic nuclear contractors will likely lead the international market of nuclear exports. “*Made in China*” may become the new international nuclear standard.

Let me remind you, though, that only regional answers exist for nuclear energy. Chinese nuclear exports will fit better in some energy ecosystems and worse in others. Let me mention the case of the UK, which is outside the OBOR initiative [oBP]. The UK has currently three major nuclear projects in the pipeline (Hinkley Point, Moorside and Wylfa) and China is already involved in one (in Hinkley Point C) and had been bidding for a second one (in Moorside) [PHZ17] & [HZ17].

Let's focus on Hinkley Point C, where 2 EPRs are planned for construction [EPR]. In 2016, the UK's government provisionally paused the project due to concerns about Chinese involvement in the UK's energy production (similar concerns have arisen in Moorside, where KEPCO has provisionally won the deal: "*Why on earth would the Foreign Office be happy to let them [China] take over NuGen [a UK nuclear company owned by Japan's Toshiba]?*") [PHZ17] & [NuG] & [WJA17].

Chinese investment was finally accepted at Hinkley Point C, so that China's CGN and CNNC would finance 1/3 of the total cost, whereas France's EDF would finance the remaining 2/3. However, China has been "*allowed to provide an investment but not much else*" and has complained that the contracts are ending up in French companies instead of in Chinese companies [PHZ17] & [HZ17]. This pro-Western strategy might be a financial miscalculation, as we discussed with the evolution of EPR's NCTs, since delays and cost overruns are already accumulating at Hinkley Point C [SW17] & [But17e]. The tables may turn around in the future Bradwell B project (CGN will provide Chinese nuclear technology alongside with 2/3 of the finance, whereas EDF will provide 1/3 of the finance [Vau17a]), but we will have to wait to verify our hypothesis.

Despite these geopolitical sensitivities in the UK, the prospects for Chinese nuclear exports are promising. Seemingly, **the national balances of the Asian emerging superpowers are in favour of nuclear energy**. The Chinese energy ecosystem indeed matches 3 nuclear internal technological strengths: its geostrategy (international nuclear exports), its profitability (even though "cost" was a potential weakness in the world, it is indeed a manifest strength in China, with its exemplary NCTs) and its low human-health impact (low air pollution). The Indian energy ecosystem matches with this last manifest strength, low human-health impact. Both countries will likely drive worldwide nuclear expansion in the next years. Nuclear energy will successfully migrate towards the Asian emerging superpowers.

*We Chinese know only too well what it takes to achieve prosperity so we applaud the achievements of others and we wish them a better future. We are not jealous of others' success and we will not complain about the others who have benefited. We will welcome them aboard the express train of Chinese development.*

*Xi Jinping*

*"Opening Plenary with Xi Jinping, President of the People's Republic of China, at the World Economic Forum Annual Meeting in Davos, 2017", [WEF]*

### 3.4.3 The former USSR states

*Do you think that —given two countries that stand at completely opposite poles— all they have to do is come together and immediately all the contradictions between them will disappear? That’s impossible. Only people living in the realm of fantasy or people who have absolutely no understanding of the class struggle could imagine such a thing. What is involved is a prolonged process, and differences cannot be settled just by friendly talks at a round table.*

*Nikita Khrushchev*

*“Memoirs of Nikita Khrushchev - Volume 3: Statesman (1953-1964)”*

From the ashes of the Union of Soviet Socialist Republics (USSR), 15 new states were born no later than 1991. They are known as Former Soviet Union (FSU) and stretch right across Eurasia, from the Baltic and Black Seas to the Pacific Ocean [CDPM]. Three of these states (Russia, Ukraine and Belarus) formed a new association on the eve of USSR’s dissolution, the Commonwealth of Independent States (CIS), that would coordinate their policies in areas such as economy, foreign policy or environmental protection [CDPM] & [oEBa]. Almost all other FSU states later joined the CIS, a CIS which Russia has always led: it accounts for 1/2 of CIS’ population, 3/4 of its GDP, 5/6 of its surface [WBP] & [Bana] & [WBP].

Russia is a worldwide *energy giant*, with extensive fossil fuel resources that are extensively exploited and traded. All fossil fuels are abundant in Russia: it holds the 2<sup>nd</sup> largest natural gas reserves in the world, the 3<sup>rd</sup> largest of coal and the 6<sup>th</sup> largest of oil [BPS17]. Russian natural gas and oil industry are a vital component of Russian economy (its domestic operations and international exports make up 1/3 of Russia’s national budget revenues [Bar17]) and a vital component of European energy supply (Russia *alone* provides 35% of all natural gas imports of Europe, 35% of its crude oil imports and 45% of its oil products imports [BPS17]).

An extensive network of pipelines transport the Russian natural gas towards Europe [BPS17]. Within this extensive network, 5 main pipelines act as backbone (Figure 3.22) and exit Russia towards the depths of the Baltic Sea and the Black Sea or towards the Belarussian and Ukranian territories [Exp].

Historically, the first Russian pipelines were developed onshore and across the CIS states, first across Ukraine and then also across Belarus. Ukraine and Belarus served as major transmission pathways: take for example 2006, the year of the first gas crisis in Ukraine [Kir14], when Ukraine transported 3/4 of all Russian exports towards Europe and Turkey [BP207] & [Naf] & [Ukr] & [SF17]. Recently, Russian pipelines have been developed offshore bypassing the previous CIS states, towards Germany under the Baltic Sea and towards Turkey under the Black Sea [Exp]. Why has Russia followed this path and how does it affect nuclear energy?

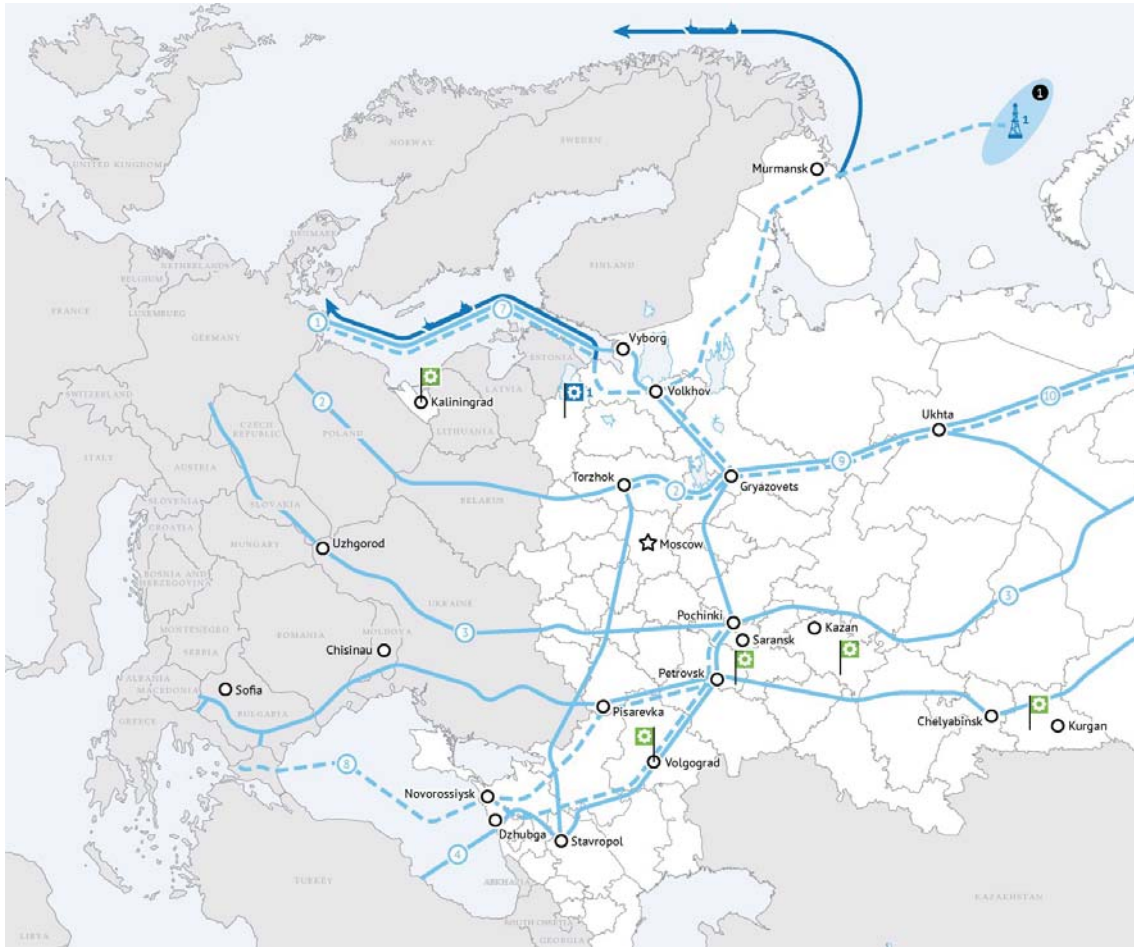


Figure 3.22: Natural gas pipelines from Russia towards Europe, at the heart of Gazprom Group’s gas business development. Naming the gas pipelines from North to South: “*Nord Stream*” and “*Nord Stream 2*” (under construction) under the Baltic Sea, “*Yamal-Europe*” across Belarus, “*Brotherhood*” and the Romanian pipeline across Ukraine and “*TurkStream*” (under construction) and “*Blue Stream*” under the Black Sea. Credit: Gazprom [Gazb]

Russia has traditionally controlled Ukraine and Belarus by controlling their energy supply, aiming to secure their loyalty as gas transmission allies. Belarus imported almost all its natural gas consumption from Russia between 1998 and 2016 [oECOi] & [IEAa], while Ukraine imported  $\approx 4/5$  of its natural gas consumption from Russia and Turkmenistan between 1998 and 2008 [oECOj] & [Naf] (2008, the second gas crisis in Ukraine [Kir14]). Alternatively, Russia promoted Ukrainian nuclear generation, which has generated  $1/2$  of its electricity since the early 2000’s [IAE17b]. All 15 Ukrainian reactors are Soviet designs (all of them started construction when the USSR was still standing [IAE17b]) and have been mostly serviced and refuelled by Russia [Assf]. As a side benefit for the then USSR, this nuclear expansion perfectly fitted the Science and Technology race during the Cold War.

However, the relations between Ukraine and Russia have deteriorated over the last decade, most remarkably after Russia annexed Crimea in 2014 and fomented a rebellion in Eastern Ukraine that is still ongoing as of November 2017 [Tho17b] & [Com17]. As expected, Ukraine has dramatically reduced its gas consumption and its dependency on Russian imports since 2011 [oECOj] & [Naf] (after its second gas crisis, before the Crimean occupation), to the point that Ukraine does not consume Russian gas *directly* from Gazprom since 2015 [Eco17b] (the year after the Crimean occupation). In parallel, Ukraine is also reducing its nuclear dependence on Russia by acquiring nuclear fuel from Westinghouse and AREVA [Assf] & [ARE].

As one of its major transmission allies, Ukraine has become “untrustworthy”. What could Russia do to guarantee its gas exports? The Russians had known the answer for years: *ensure Belorussian loyalty, diversify Russian gas routes and diversify Russian gas markets*.

First, aiming to *ensure Belorussian loyalty*, Russia is expanding its energy influence over Belarus. As for natural gas, Gazprom successively increased its stake in Beltranz, the operator of the Belorussian section of the “Yamal-Europe” pipeline, until becoming its sole owner in 2011 and renaming it as Gazprom Transgaz Belarus in 2013 [Gaza] & [Bel]. As for electricity, gas-fired generation currently dominates Belorussian generation [IEAb], which in other words means that Russian gas currently dominates Belorussian electricity generation. In parallel, the “Belorussians” are building its first 2 nuclear reactors, financed by Russia [Assc] and designed and built by Russia’s ROSATOM [Pee17]. As Russia (and the USSR) previously did with Ukraine, Russia is controlling how nuclear energy looks like in Belarus.

Second, aiming to *diversify Russian gas routes*, Russia has been expanding its gas routes towards Europe and Turkey bypassing Ukraine, even though its operational gas pipelines are underutilised [Vat17]. In this line, Russia has been focusing on 4 offshore pipelines (2 operational, 2 under construction) towards its biggest customers in the region: Germany and Turkey [BPS17]. Recent US sanctions and German electoral results may increase the time and cost of this diversification, but may not impede its completion [KdC17] & [CB17]. The Oxford Institute for Energy Studies hints that Russia would still need Ukrainian transit after 2019 (when the current transit contract expires), but Ukraine will play a lesser role than in recent years [Oxf16] & [Naf]. At last, there is an additional, financial advantage to bypassing Ukraine: less transit fees for Russia [Eco17b] & [CB17].

Third, aiming to *diversify Russian gas markets*, Gazprom is looking outside Europe. In a time when Europe, Turkey and CIS altogether account for 9/10 of all Russian natural gas exports [BPS17]. But also in a time when non-Russian LNG supplies to Europe may threaten Russian dominance [SF17]. In this context, Gazprom is also looking East, towards the Chinese market, with “several pipelines in the pipeline” (“Power of Siberia” and maybe “Power of Siberia 2” [Gazb] & [AK17]).

All in all, the three CIS' founding members (Russia, Ukraine and Belarus) have largely determined European energy security with its exports of natural gas, crude oil and oil products. All these exports originated in Russia and, traditionally for natural gas, transited via Ukraine and Belarus before reaching the European market, the stronghold of Russian energy exports. Russia controlled the loyalty of these transit countries by controlling their energy supply: evidently their natural gas consumption, but additionally their nuclear energy (since long in Ukraine, since recently in Belarus).

The former USSR and the present-day Russia have financed, designed, built and serviced the Ukrainian nuclear reactors. Belorussian nuclear reactors are about to follow the same path. Although Russia is pursuing diversification strategies by-passing Ukraine (alternative routes, alternative markets) and Ukraine is following suit (alternative nuclear service providers), the Russian-controlled nuclear energy is still a powerful loyalty instrument. Accordingly, the Russian energy ecosystem matches with one nuclear internal strength: **geostrategy** (boosting technology knowledge and exports).

Russian nuclear development spreads beyond Ukraine and Belarus. Do you remember that Vyacheslav Pershukov, from ROSATOM's Management Board, reportedly suggested that the nuclear export market had been exhausted? [Cot17b]. Let me clarify this statement. *Maybe* this means that ROSATOM will not significantly expand abroad *beyond its current backlog*. But *surely* this does *not* mean that ROSATOM is not expanding abroad right now: ROSATOM leads the current ranking of more nuclear construction projects in the world (8 in Russia and 34 abroad) [ROS]. All these projects spread across 12 countries, mostly outside Russia, in accordance with Russia's geostrategy to increase its international influence by controlling international energy supplies.

Some of ROSATOM's projects are under construction (such as in Belarus, Bangladesh, China or India) while some of them are planned for construction (such as in Finland, Hungary, Turkey or Iran) [Foy17] & [ROS]. Let me highlight two cases beyond the Belorussian one: the case for the OPEC and the case for Turkey.

As for the OPEC countries, ROSATOM has ongoing projects or agreements in place in 3 OPEC members: in Saudi Arabia, Iran and Nigeria [Foy17] & [New]. These 3 OPEC members together with Russia account for 2/5 of all the crude oil trade in the world [BPS17] & [OPE17]. Among them, the largest exporters are Russia and Saudi Arabia, which are closely cooperating in worldwide oil supply cuts and are becoming increasingly bound for economic and political reasons [RF17] & [Rav17b]. In this line, if you combine Saudi Arabian "Vision 2030" to diversify its economy [Vis] and Russian tendency to export nuclear reactors to geostrategic allies, ROSATOM's cooperation with Saudi Arabia seems simply convenient. ROSATOM's exports to Iran and Nigeria may well point in a similar direction.



As for Turkey, it is the 2<sup>nd</sup> largest importer of Russian gas in the world [BPS17], is involved in 2 offshore Russian pipelines under the Black Sea and one of these pipelines (“TurkStream”) will transport Russian gas towards Turkey and towards Southern and Southeastern *Europe* [Gaze]... Russia is financing the first Turkish nuclear reactors and ROSATOM will design, build and even operate them [Sta17c]... This is just one more episode of the same story.

In essence, **the national balances of the former USSR states (driven by Russia) are in favour of nuclear energy**. Neither the Chernobyl accident (in present-day Ukraine) nor Russian public opinion (against nuclear energy [Bla11]) shape Russian nuclear policy. Instead, it is shaped by 1 manifest strength, geostrategy (boosting technology knowledge and exports). As Chinese nuclear policy is targeting mainly OBOR countries, the Russian one is targeting mainly its international allies in fossil fuel exports. Although Russia has reduced its projections for domestic nuclear expansion, ROSATOM is “filling this gap” abroad and will compete with Chinese nuclear companies for the largest share of world nuclear exports. “*Made in Russia*” may too become the new international nuclear standard.

*Advanced energy acceleration may transform energy diplomacy. In today’s world, energy security derives from access to resources (e.g. physical control or reliable access to coal, crude oil, or uranium), as well as the supporting energy supply chain and infrastructure. In tomorrow’s world, energy security may instead come from access to technology.*

*World Economic Forum, McKinsey & Company*

*“Game Changers in the Energy System - Emerging Themes Reshaping the Energy Landscape”, [WEF17a]*



Figure 3.23: Russia’s president Vladimir Putin (right) meets with Gazprom’s CEO Alexei Miller (left) in Moscow, 2012. Credit: Business Insider [Hir15]

### 3.5 Beneath the West: Western countries' balances

*For me, it is far better to grasp the Universe as it really is than to persist in delusion, however satisfying and reassuring.*

*Carl Sagan*

*“The Demon-Haunted World: Science as a Candle in the Dark”*

The West encompasses several long-standing leaders (namely the US, Canada, the UK, France and Germany) and no relative newcomers (only countries with established and stagnated nuclear generation are building reactors in the West [IAE17b]).

Let's focus on these 5 long-standing leaders. They summarise the West: they account for  $\approx 80\%$  of Western reactors and net electrical capacity in operation, their fleets are ageing (35 operational years on average) and have no generational replacement in sight (only 3 reactors under construction in these 5 countries, only 6 reactors under construction in the whole West) [IAE17b] & [Ageg]. We can hence accurately model the West with the national balances of these 5 countries. Besides, these national balances, albeit diverse, show relatively similar common patters. We can hence model the West with only 1 geographical cluster: the Western long-standing leaders (Figure 3.24). The West: 1 cluster & 5 countries.

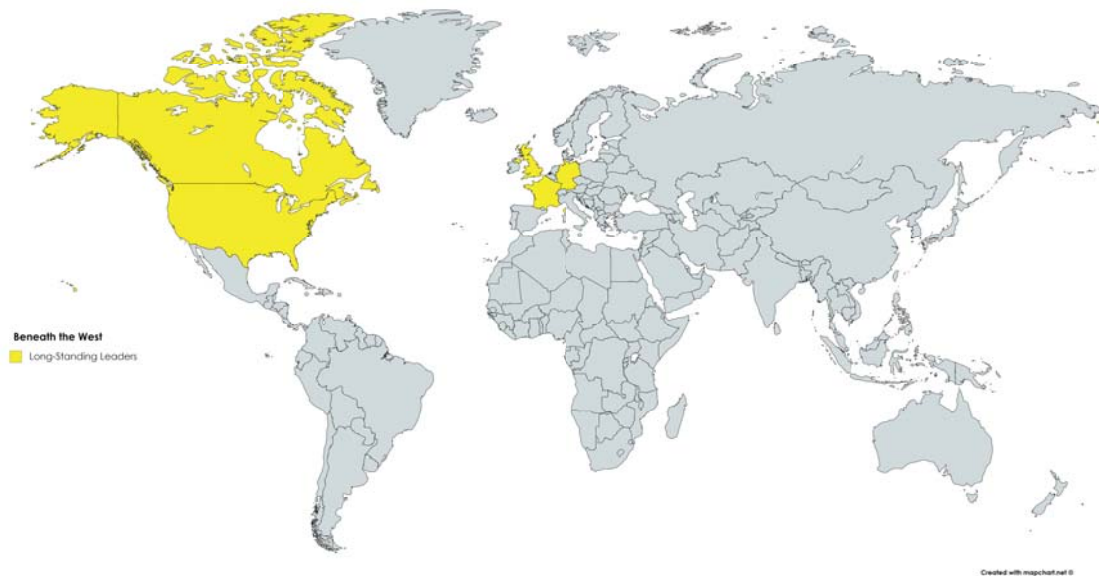


Figure 3.24: One geographical cluster of national balances in the West: the Western long-standing leaders (the US, Canada, the UK, France and Germany). There are 3 more Western nuclear countries with less significant roles (Sweden, Spain and Belgium) and 7 more with minor roles, not highlighted in this graph and not individually covered in the following analysis. Map created with MapChart [Map]

The US, Canada, the UK, France and Germany are developed, industrialised democracies. They account for 2/5 of global GDP [Bana] and have been members of the “Group of Seven” or “G7” (together with Italy and Japan) since the mid 1970’s. Back then, this forum became a venue for non-Communist powers to coordinate their economic, security and energy policies [oFR]. Cold War politics and, by extension, nuclear politics invariably entered the G7 agenda [oFR]. Look at this coincidence: in 1990, (only) “*for technical and economic reasons*”, the recently-unified Germany shut down all Soviet reactors in the former-Communist East Germany, so that only non-Soviet reactors remained operational in the former-non-Communist West Germany [Sta11] & [Assb] & [Agea].

Cold War’s Science and Technology race was one driver of Western nuclear development. The 1973’s and 1979’s oil crises were two more drivers, because they revealed Western energy dependence on OPEC [Mac11]. Let’s compare the *completed* construction starts (discarding cancelled ones) in the West before and after 1973: 105 GW between 1963 and 1972 compared to 152 GW between 1973 and 1982, a 45% decade-to-decade increase [IAE17b].

As you can see, *geostrategy* became the most manifest strength back then: boosting technology knowledge and exports during the Cold War, limiting geopolitical vulnerability against OPEC. *Cost* overruns did not halt this growth, even though they afflicted 129 reactors in a sample of 133 US and French reactors (between 1969 and 1993), with average cost overruns over 130% per reactor [SGN14].

Nonetheless, 1979’s TMI and 1986’s Chernobyl outweighed the previous drivers. *Safety* became a manifest weakness. Completed construction starts vanished: only 13 GW between 1983 and 1992, a 91% decade-to-decade decline [IAE17b]. Construction cancellations multiplied: 53 reactors were cancelled between 1979 and 1993 and were never finished [Aged]. Even after Chernobyl, the West has dominated worldwide nuclear cumulative capacity. But purely by inertia. It is ageing, declining.

Nowadays, the Western energy ecosystem *mismatches* with nuclear energy. On one hand, its potential strengths remain *almost* invisible and do not manifest: they are mostly solving “invisible problems” and have plenty of competition from other energy species to solve them. On the other hand, its potential weaknesses become visible and manifest: they are clashing with “visible problems” in a way unknown for any other energy species.

In a metaphorical sense, Western nuclear energy incarnates the antithesis of Achilles, the mythological hero that besieges Troy in the “Iliad”. While Iliad’s Achilles has several visible strengths and few “invisible” weaknesses (most notably, his heel, his only vulnerable spot), Western nuclear energy is the opposite story, it has invisible strengths and visible weaknesses. We could imagine nuclear energy as the “*Anti-Achilles*” in the Western energy ecosystem.

### 3.5.1 Invisible strengths solving invisible problems

Concerning **environmental impacts**, Western long-standing leaders have less land footprint constraints for electricity generation (compared to the Far Eastern small states) and are rapidly deploying other low-GHG electricity sources (among the most extensive deployments worldwide).

If we focus on land footprint, their national electricity densities are lower than Japan's value (which, in turn, was the lowest among all Far Eastern small states). Coming back to the analysis behind Figure 3.11, Germany, the UK and France (European countries with small surfaces) have electricity densities between 40% and 70% of Japan's value, whereas the US and Canada (North American countries with huge surfaces) have them below 20% of Japan's value. Moreover, they can internationally exchange electricity with its neighbouring countries [ENT17] & [Adma], in contrast to the isolated Far Eastern small states. Therefore, Western long-standing leaders do not value the low land footprint of nuclear electricity generation.

If we focus on GHG emissions, they are among the worldwide leaders in renewable electricity generation, as depicted in Figure 3.25. These renewable electricity sources are as clean in GHG terms as nuclear energy (all of them have some of the lowest lifecycle CO<sub>2</sub>-equivalent emissions per electrical MWh [TBA13]) and thus nuclear energy has no competitive advantage in GHG terms against renewable energy.

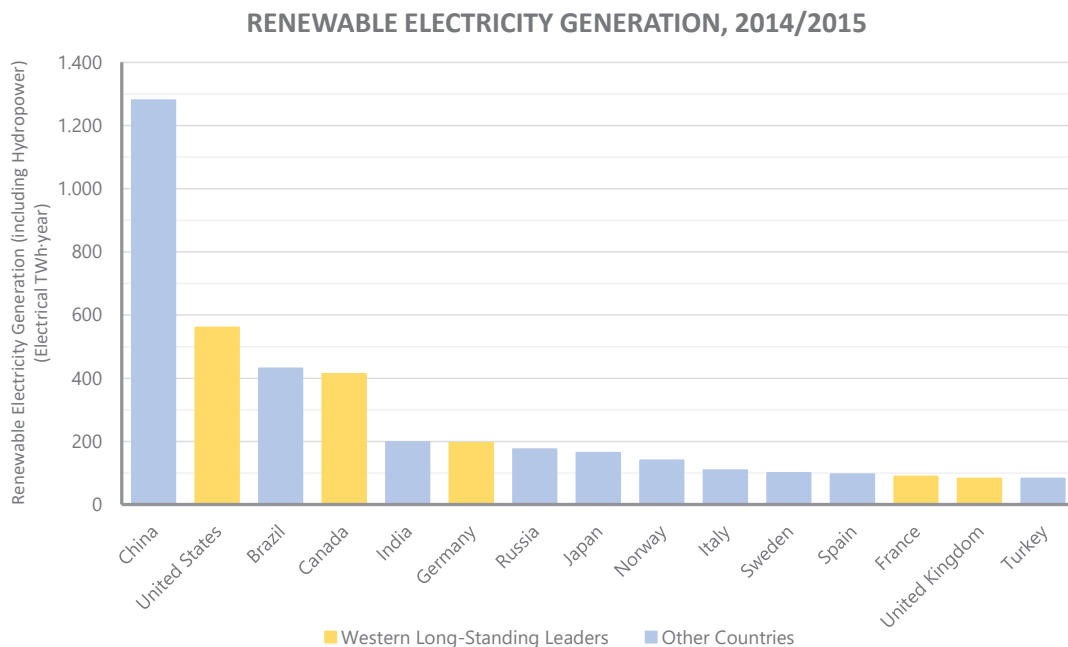


Figure 3.25: Renewable electricity generation, in TWh per year. We computed it for all individual countries in [WBRc] and depict it for the highest 15 values (3/4 of worldwide renewable electricity). The 5 Western long-standing leaders are among them and account for 1/4 of worldwide renewable electricity. Electricity consumption from renewable sources (excluding hydroelectric sources) from The World Bank [WBRc] & [WBRb], electricity consumption from hydroelectric sources from The World Bank [WBRa]. Data for 2015 and, if missing, data for 2014

Concerning **human-health impacts**, their air pollution levels (in terms of PM2.5) are much lower than Eastern and Southern Asia's values, as depicted in Figure 3.26. The 5 Western long-standing leaders, as well as the European Union as a whole, consistently outperform the world average: less than 1/2 of the world average PM2.5 levels in the 1990's, less than 1/3 in the 2010's. Conversely, Eastern and Southern Asia consistently underperform the world average: more than 1.2 times the world average PM2.5 levels in the 1990's, more than 1.3 times (and up to 2 times) in the 2010's. Accordingly, air pollution is a major driver of nuclear energy expansion in the Asian emerging superpowers, but not in the West.

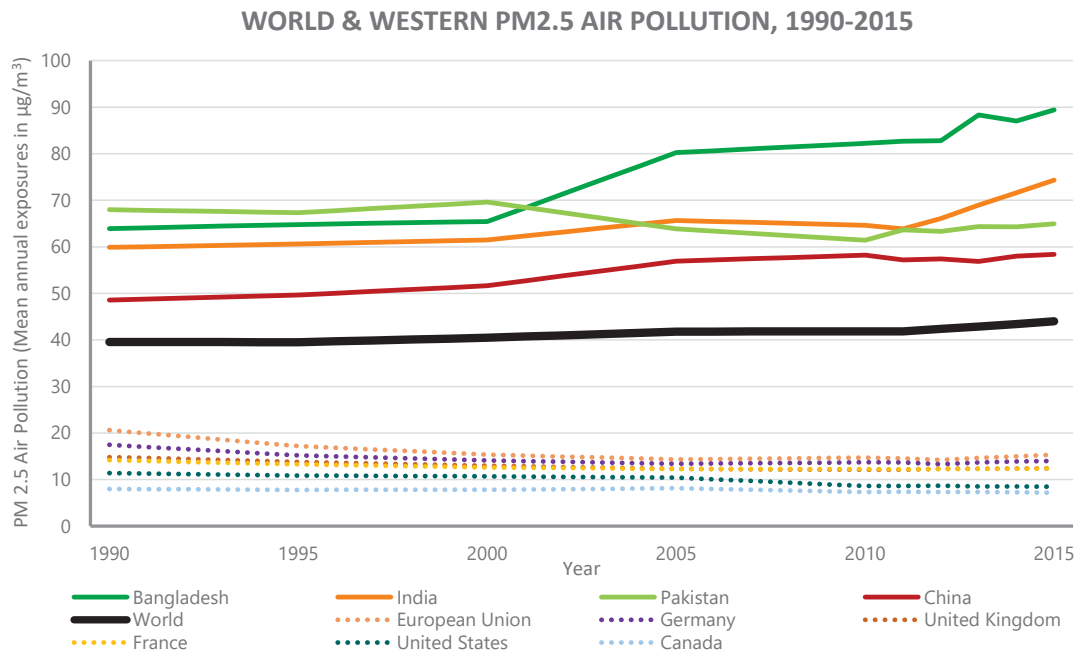


Figure 3.26: Population-weighted exposures to ambient PM2.5 (average of *local* PM2.5 exposures weighted by corresponding *local* populations [ea17a]), expressed in  $\mu\text{g}/\text{m}^3$ . We depict this indicator for the largest, most polluted countries in Eastern and Southern Asia, as well as the Western long-standing leaders and the whole European Union. If a country is always above the world average, it is depicted as solid line (otherwise, as dotted line). Data from The World Bank (5-year averages from 1990 until 2010, 1-year averages from 2010 until 2015) [WBAb]

Concerning **grid security**, the Western long-standing leaders have fossil and renewable electricity sources that are at least as dispatchable as nuclear energy and than can contribute to the grid frequency control at least as much as nuclear energy.

Let's focus on the most recent problem: the grid integration of *variable* renewable energy (VRE), comprising wind and solar PV. Wind and solar PV can compromise grid stability, even if their share of generation is low. The ease of

VRE integration varies from one national grid to another, although 15%-25% shares of VRE typically require additional fossil-fuel flexibility and more interconnections [IRE17a]. Only Germany (18.7%) and the UK (14.9%) were close *on a yearly basis* in 2016 to those VRE shares [ENT17]. Germany had even higher VRE shares according to Fraunhofer ISE, as high as 21.4% in 2016 [fSESc] & [fSESB]. Let's focus thus only on Germany and the UK, because the US, Canada and France have far lower VRE shares [WBRb].

Nuclear energy offers *no* competitive advantage in grid security terms in Germany and the UK. Take the year 2016 as example. Both countries had large shares of fossil-fuel installed capacity (1/2 in the UK [DUK17], 2/5 in Germany [fSESd]) and, at the same time, low fossil-fuel capacity factors (around 40% in the UK [DUK17] and in Germany [fSESd] & [fSESa]). Consequently, both countries had a great deal of fossil-fuel spare capacity to control load and frequency variations. We will neglect other dispatchable, non-fossil sources such as hydropower or biomass (they are minor sources in these two countries [IEAc] & [IEAe]) and we will assume no transmission and distribution network constraints as a first approximation.

All the aforementioned fossil-fuel capacity is at least as flexible as nuclear capacity. Coal-fired plants are more or less as flexible as nuclear reactors (in terms of minimum loads and load rates), while gas-fired plants are either as flexible or more flexible than nuclear reactors (in terms of minimum loads and load rates) [HBS16] & [OEC11]. As if all this were not enough, Germany is net exporter of electricity (in 2016, net exports were 8.1% of its domestic generation [ENT17]) and could reduce these electricity exports if needed for its domestic grid security. In a nutshell, neither Germany nor the UK (nor the remaining Western long-standing leaders) inevitably need nuclear generation to guarantee its grid security.

Concerning **geostrategy**, the West is fragmented concerning nuclear energy. We will start analysing what's common and progress towards what's genuine of each national balance. Let's start with gross exports, since these 5 Western long-standing leaders share an exporting passion: they rank between the 2<sup>nd</sup> and 12<sup>th</sup> largest gross exports on the global scale and are particularly keen on exporting machines, transportation goods and chemicals [oECO<sub>h</sub>] & [oECO<sub>a</sub>] & [oECO<sub>c</sub>] & [oECO<sub>d</sub>] & [oECO<sub>g</sub>]. Theoretically, these 5 countries may want also to export their domestic nuclear designs, but in practice only 2 of them are in a position to export them: the US (via Westinghouse-Toshiba and GE-Hitachi, that are owned by or cooperate with Japanese companies) and France (via AREVA).

Notwithstanding, these 3 nuclear companies are performing poorly both inland and overseas. Their construction figures are dismal. Andrew Ward, Energy Editor at Financial Times, wrote ironically: *"It sometimes seems like US and European nuclear companies are in competition to see which can heap greater embarrassment on their industry"* [War17h].

*GE-Hitachi* is building 0 reactors inland and 3 overseas (2 in Taiwan, 1 in Japan) and all are virtually suspended [IAE17b] & [Aged]. Taiwan's ones started construction in 1999, but have been a managerial and political nightmare to the point that have not started up and their future looks gloomy considering that Taiwan will phase out nuclear energy in 2025 [Asse] & [Eco17d]. Japan's one started construction in 2007, but its construction was halted by Fukushima and has not restarted yet [Assd]. One project in the UK recently received green light after 5 years of regulatory proceedings and £2 billion of investment, but we must wait to confirm if it runs more smoothly than the recent GE-Hitachi records [Vau17b] & [Pow].

*Westinghouse-Toshiba* is building 4 reactors inland and 4 overseas (in China) [IAE17b] & [Aged]. All are delayed more than 3 years and, at least in the US, are accumulating billions of cost overruns, to the point that 2 of the US reactors recently suspended construction [CI17] & [Sta17d] & [War17l]. The client companies were publicly disenchanted: *"In choosing Westinghouse, [we] chose a company with a worldwide reputation as the clear leader in nuclear design and engineering. Unfortunately, Westinghouse failed to live up to its reputation and perform"* [War17l]. Months before the suspension, Westinghouse had filed for bankruptcy protection and forced its parent company Toshiba into serious financial trouble [War17e] & [ILC17]. As you see, the future of Westinghouse-Toshiba is obscure.

China can help to a lesser extent. They can soon prove the operational performance of Westinghouse new reactors (if successful, international orders may increase for Westinghouse), but the US government will *not* allow the Chinese (nor the Russian) to buy the financial-troubled Westinghouse [SG17] & [CS17] & [War17d].

The US government may help looking for buyers or even by offering governmental support to retain Westinghouse under US control: *"We clearly have been having discussions in the White House about Westinghouse and about the future of nuclear and the future of having more than one US-based nuclear power manufacturer"* [SJC17b]. Seemingly, Westinghouse will end up in Canadian hands [Cro18a].

Rick Perry, US energy secretary, went even further: *"It's a lot bigger than just making sure that Westinghouse continues to be a stable American company. This is a massively important issue for the security of America and the security for America's allies"*. Rick Perry was most probably worried about technology transfer issues, the fact that Westinghouse supplies technology for US Navy nuclear submarines and the fact that China and Russia will fill the void in the nuclear exports market [SJC17b].

*AREVA* is building 1 reactor inland and 3 overseas (2 in China, 1 in Finland) and 2 more UK projects are imminently in the pipeline [IAE17b] & [Aged]. We have extensively spoken about them: their months and years of delays and their billions in cost overruns (the latter at least for the European projects). The only good news come from China, where 2 EPRs are only months delayed and near completion.

AREVA is changing hands and changing strategy. In 2016, AREVA (almost completely owned by France) was forced into a 5 billion € state-backed rescue and in 2017 EDF (almost completely owned by France) agreed to purchase a majority stake in AREVA’s nuclear division [Keo17a] & [CK17a]. In parallel, the French government has been pressing EDF for a precise plan to shift from nuclear towards renewables and has set to reduce French share of nuclear generation from 75% nowadays to 50% in 2035 [CK17a]. In the words of Nicolas Hulot, France’s Energy and Environment minister: *“Tomorrow the norm must no longer be nuclear power but renewable energy. It’s a complete overhaul of our model”* [CK17a]. Evidently, the future for AREVA is, at the very least, mired in uncertainty.

None of the 3 Western nuclear designers will likely increase its nuclear exports as much as the Eastern counterparts. They will likely survive in the coming years, but will *not* likely prosper. Consequently, boosting technology knowledge and exports will not become a manifest strength in the Western long-standing leaders, except for the US, that surely values nuclear technology *knowledge*.

What about the other side of geostrategy, concerning the hedge against energy imports? In this sense, the Atlantic Ocean draws a first separation in the West.

On the North American side, Canada has been net energy exporter since 1970 and the US has been decreasing its net energy exports lately: in the decade between 2005 and 2015, the US reduced its net energy imports from 30% of its net energy use to 7% [WBEa]. In the near future, the US becomes net energy exporter in most EIA’s scenarios, as oil imports fall and natural gas exports rise [Admb]. Fatih Birol, IEA’s executive director, even declared that *“the US will become the undisputed global oil and gas leader for decades to come”* [RW17]. The US holds the 2<sup>nd</sup> largest reserves of coal in the world and the 5<sup>th</sup> largest of natural gas, while Canada holds the 3<sup>rd</sup> largest of oil [BPS17]. The US and Canada will not value the “nuclear hedge” against trade fluctuations.

On the European side, the European Union imported 50% of its net energy use year after year between 2005 and 2015 [WBEa]. France’s and Germany’s net imports remained roughly stable and close the European Union average, while the UK oscillated (increased, peaked and decreased) always below the European Union average [WBEa]. These 3 countries have almost non-existent reserves of fossil fuels, except for coal in Germany (6<sup>th</sup> largest in the world), and have multiple supplying countries for their fossil-fuel imports [BPS17].

The UK, France and Germany may value this “nuclear hedge” against trade fluctuations and thus geostrategy *may* be the only potential strength that becomes manifest for them. It becomes manifest, but only *to a lesser extent*: these 3 countries have in parallel some of the largest “renewable hedges” in the world (in absolute terms, as Figure 3.25 depicts), which are even more robust against trade fluctuations.



A further division in Europe sets Germany apart from the UK and France: Germany's plentiful reserves of low-graded coal (Figure 3.27). This low-graded coal has no functioning international trade: it is mostly utilised close to the mines (due to its higher water content and, hence, its smaller lower heating value) and is almost always used for electricity generation [WEC16b]. Therefore, the UK and France value this “nuclear hedge” more than Germany, which has its own “domestic coal hedge”. Germany, more or less publicly, gives priority to this “domestic coal hedge”.



Figure 3.27: Bucket-wheel excavators mining brown coal at the Inden opencast mine, Germany. Image from Wikimedia Commons. Photo by CEphoto, Uwe Aranas [CEp]

In a nutshell, almost all potential strengths remain invisible: **Western nuclear energy is “solving” invisible problems with plenty of competition to solve them.** As for *environmental impacts*, the Western long-standing leaders have less land footprint constraints (compared to the Far Eastern small states) and are rapidly deploying other low-GHG electricity sources. As for *human-health impacts*, their air pollution levels are very low (compared to Eastern and Southern Asia). As for *grid security*, they have abundant fossil-fuel capacity at least as dispatchable and as suitable for grid frequency control as nuclear energy. As for *geostrategy*, they will not increase nuclear exports as much as the Eastern counterparts (although the US values nuclear technological knowledge) and they already have some of the largest “renewable hedges” against trade fluctuations (although the UK and France value the “nuclear hedge”).

### 3.5.2 Visible weaknesses clashing with visible problems

Concerning **costs**, Western nuclear reactors are financially problematic, regardless of their status (planned, under construction, operational or shut down). Nuclear energy is “the least agile energy source” in financial terms, the “Goliath” among all energy sources. It has long lead times for development and construction, correlated with long payback periods and huge upfront costs (typically compounded by overruns and delays) and complemented by uncertain decommissioning costs. The West is unanimously shying away from these less agile, “Goliath-like finances” and is embracing more agile, “David-like finances” (Figure 3.28).



Figure 3.28: “David and Goliath”, inspired by the Old Testament passage 1 Sam 17 and painted by Caravaggio around 1599. Image from Wikipedia [Car]

The wind and solar PV boom is pushing the Western energy ecosystem towards “David-like finances” and away from the “Goliath-like finances” of *new* nuclear reactors. In the words of Alberto Gandolfi, head of European Utilities Research at Goldman Sachs: “*What started as a decarbonisation process thanks to better technology is about to become a process driven by costs and the economics*” [Sac]. In the coming years, the IEA projects that renewables led by wind and solar will even become the cheapest electricity source in many countries [RW17].

Renewable costs are diminishing ( $-4/5$  for solar panels and  $-1/3$  for wind turbines between 2009 and 2017) while their policy support is spreading (present in around 146 countries at the beginning of 2017, nearly triple the number of 2004) [Cla17a]. Furthermore, renewable costs are modular, both for manufacturing and installation, and agile: smaller installed capacities per farm [Win16] with shorter construction times and shorter lifetimes [Sol] & [Hun]. This is how “David-like finances” look now: diminishing costs that are policy-supported, modular and agile.

“David-like finances” offer competitive advantages over “Goliath-like finances” and most remarkably during an energy transition. First, consider the smaller installed capacities per wind or solar farm, with lower upfront investments and diverse financing schemes. They likely translate into more potential investors.

Second, consider their modularity and shorter construction times, which depend less on Civil Engineering. They likely translate into better project execution: less construction delays and cost overruns, which severely affect Western nuclear reactors and worldwide energy and infrastructure projects [Smy16b] & [Cro17c] & [Eco17a]. The 4 nuclear reactors under construction in the Western long-standing leaders are years delayed and billions over budget. Further examples are Hinkley Point C, where EDF has demanded a premium for shouldering the construction risk [War17g], and VC Summer, suspended after billions of cost overruns but open to new funding sources “*to see if we can make the project economical again*” [War17l].

Third, consider their shorter lifetimes combined with the policy support for low-carbon technologies. They likely translate into more robustness against a transitioning energy ecosystem: less risk of becoming stranded assets (assets that suffer from unanticipated or premature devaluations due to market or regulatory changes [IEA17c]) and less capital losses if they do (lower investments per farm and more potential investors, which translates into lower potential losses for each investor).

*Although there are advantages to having scale, it is becoming more difficult for large players to shape and manage market outcomes [...] Agility has become more important partly because world markets, and therefore the end-use markets for energy, have become more volatile. In the face of greater uncertainty, it can be risky and, over time, value destroying to bet billions of dollars on assets that must live productively for 30 years. In contrast, agility – small initial footprints, investments in real optionality to monitor markets for a couple years before deciding how best to grow, the capability to rapidly adjust – is a better fit for a highly volatile world.*

*World Economic Forum, McKinsey & Company*

*“Game Changers in the Energy System - Emerging Themes Reshaping the Energy Landscape”, [WEF17a]*

A solution to low nuclear construction in the West could be widespread life extensions of operational reactors, which is what MIT envisioned for nuclear fleets in developed countries after Fukushima [MIT12]. However, *operational* reactors are also under financial threat if they continue operation, because growing competition from renewables and gas-fired plants is driving down electricity market prices. This growing competition is especially acute in the US after the shale boom [War17h] & [Ros17] & [Cro17b], although a relatively similar financial threat may arise in Germany and the UK due to their high and increasing VRE shares [WBRb]. In the words of Seneca: “*Sometimes even to live is an act of courage*”.

Let’s focus on the US. Recently, four US’ states that shuttered nuclear reactors turned to gas and coal [Ros17] and Three Mile Island will retire prematurely, in 2019, unless the state of Pennsylvania introduced “needed policy reforms” (probably as states of Illinois and New York did to keep their reactors open) [Cro17j].

At the end of 2017, Rick Perry, US energy secretary, asked the Federal Energy Regulatory Commission (FERC) to create new policy measures “*to ensure that certain reliability and resilience attributes of electric generation resources are fully valued*” or, in other words, to create new subsidies for coal-fired plants and nuclear reactors to prevent their closure [Cro17g]. However, the FERC rejected these new subsidies: the FERC could not prove that US electricity prices were “unjust and unreasonable”, which was the legal requirement to carry forward the proposal under the Federal Power Act [Cro18b]. As a consequence, no new subsidies will promote coal-fired plants and nuclear reactors in the US for the time being.

A solution to (and consequence of) costly operational reactors in the West could be the widespread shutdown of non-profitable operational reactors. However, *shut down* reactors face financial uncertainty due to the limited amount of reliable and comparable information on decommissioning costs [OEC16].

Decommissioning uncertainty is a more pressing problem in the West, since it concentrates the majority of worldwide shut down reactors and of older living reactors. Beneath the West, let’s focus on the Western European long-standing leaders, whose expertise in nuclear decommissioning is minimal [But17d]. Unsurprisingly, this minimal expertise translates into very different cost estimations per country: the estimated costs per GW decommissioned vary in a factor of 5 between France and Germany and in a factor of 9 between France and the UK [Dor].

Decommissioning budgets are vague, but substantial in any case. As for France, some of its reactors should start decommissioning in the next decade. The future decommissioning cost of all its 58 reactors is estimated at 54 billion € [But17d]. As for Germany, all its operational reactors are closing between 2011’s Fukushima and 2022. The German government estimates a cost of 38 billion € to decommission them [But17d]. As for the UK, the clean-up of 17 early nuclear sites (not only reac-

tors) may cost £119 billion (different assumptions yield figures between £97 billion and £222 billion) and its execution will spread across the next 120 years [Aut].

In a nutshell, Western nuclear reactors are financially problematic, regardless of their status: the “Goliath-like finances” of *new* reactors are mismatching the preferred “David-like finances”, *operational* reactors are threatened by growing competition of renewables and gas (mainly in the US, presumably in Germany and the UK) and *shut down* reactors are mired with financial uncertainty due to minimal decommissioning experience. As a consequence, Western nuclear energy does not verify two of Warren Buffet’s basic investment rules: “*Rule number 1: Never lose money. Rule number 2: Never forget rule number 1*” [Loi].

Imagine that this financial mismatch is somehow solved. What about the other weaknesses: safety, proliferation and waste? Are they “visible” in the West? Yes.

Concerning **safety**, several countries worldwide changed their nuclear policies after Fukushima. The most immediate responses came almost exclusively from Western Europe, whereas no responses came from North America [OEC17]. The German government promised to shut down all of its reactors by the end of 2022 and the Belgian government cancelled life extensions for its oldest reactors, while Swiss and Italian voters rejected new nuclear reactors beyond the already operational (5 in the case of Switzerland, 0 in the case of Italy) [OEC17] & [Atk17]. Recent policy changes in France away from nuclear energy are not direct consequences of Fukushima, but are influenced by Fukushima [OEC17] & [CK17a].

Is Western Europe overreacting because its nuclear energy *is* less safe than anywhere else? Not necessarily. While regulating nuclear safety is a national responsibility, all the EU countries theoretically operate nuclear facilities following the basic principles set internationally [ECS12] & [136]. After 2011’s Fukushima, all national regulators in the European Union carried out “stress tests” on all its operational reactors and concluded that none of them had to shut down for technical reasons (although practically all of them needed technical upgrades for safety purposes) [ECS12]. A couple of years later, in 2014, the European Union amended its Nuclear Safety Directive to enhance nuclear safety during the whole lifecycle of its nuclear reactors and its implementation is under way [Comb].

Is Western Europe overreacting because its nuclear energy *is perceived* less safe than anywhere else? Maybe. One reason behind Germany’s nuclear phase-out is that “*although the risks associated with nuclear energy may not have changed owing to the events in Fukushima, the way these risks are perceived has*” [Gerb]. A plausible explanation is that Western Europeans fear the most nuclear accidents because they have lost touch with catastrophic events. They live in an extended welfare system with very few natural disasters [RE)b] & [RE)a], no recent wars, low gun ownership [Kot16], few homicides [WBH] and isolated terrorism events [iD]. Thus,



Western Europeans fear the most all sorts of catastrophic events, including nuclear catastrophes: nuclear accidents as well as nuclear weapons (the latter concerning **proliferation**). Similar risks worldwide, biased perception in the West.

Concerning **waste**, the panorama is even more uncertain than for decommissioning: the further we travel into the fuel cycle, the less experience we have. Will we favour open fuel cycles (less proliferation risks and costs in the short term) or closed fuel cycles (less resource utilisation) [MIT03] & [MIT09]? Will we favour waste isolation for hundreds of thousands of years or waste transmutation [Cen]? Will we favour more reversible final storage (such as in the US or France) or less reversible final storage (such as in Finland, which is nowadays drilling its deep geological repository) [Eco17c]? Will we favour mined repositories or deep boreholes for final repositories [Assg]? Where will we drill each of the final repositories?

Each country or region must answer these questions, but only few countries are answering them. In the words of IAEA: *“Spent fuel is differently regarded by countries - as a resource by some and as a waste by others - and the strategies for its management vary. No country has a geological repository for spent fuel storage or disposal. Neither have most countries decided on a final destination for spent fuel”* [Agec]. Few answers and each with its genuine national stakeholders: more public support in Finland, less public support in France and Sweden and less policy discipline in the US [Eco17c] & [263].

Nuclear waste remains unanswered and uncertain. This uncertainty undermines nuclear energy worldwide and more alarmingly in the West, because its nuclear mismatch is (psychologically) compounded. This phenomenon is called confirmation bias, the “tendency to process information by looking for, or interpreting, information that is consistent with one’s existing beliefs” [Cas]. Nuclear energy in the West has mainly invisible advantages and visible weaknesses and hence the “most probable” existing belief is *against* nuclear energy. Accordingly, this existing belief *against* nuclear energy biases the West to worry more about waste than the East. Similar waste problem worldwide, biased perception in the West.

In essence, all potential weaknesses are visible: **Western nuclear energy is clashing with “visible problems” in a way unknown to any other energy species, most notably in Western Europe.** As for *cost*, the “Goliath-like finances” of *new* reactors are mismatching the preferred “David-like finances”, *operational* reactors are threatened by growing competition of renewables and gas (mainly in the US, presumably in Germany and the UK) and *shut down* reactors are mired with financial uncertainty due to minimal decommissioning experience. As for *safety* and *proliferation*, the Western Europeans have lost touch with catastrophic events, hence fear them the most and hence fear nuclear accidents and nuclear weapons the most. As for *waste*, it is an uncertain problem worldwide that the Western confirmation bias perceives as more alarming.

## 3.6 The nuclear species: survival perspectives

*Why do people move? What makes them uproot and leave everything they've known for a great unknown beyond the horizon? Why climb this Mount Everest of formalities that makes you feel like a beggar? Why enter this jungle of foreignness where everything is new, strange and difficult? The answer is the same the world over: people move in hope of a better life.*

*Y. Martel*

*“Life of Pi”*

Nuclear energy will doubtlessly not reach the 2025 targets and will most probably not reach the 2050 targets of IAEA's and IEA's most ambitious scenarios. Why are the possible and the actual still so far apart on the global stage?

On the *global level*, it is because two different sides of the world are pulling in two different directions. Nuclear energy is withering in the nuclear-leading half of the world, whereas it is -only slowly- gathering pace in the nuclear-emerging half of the world. “Nascent” reactors will be born in the East in higher number and with higher speed, “living” reactors are younger in the East and “deceased” reactors lived longer in the East. In other words, **nuclear energy as energy species is migrating from the West towards the East.**

On the *regional level*, it is because the Eastern energy ecosystem matches better nuclear energy as energy species than the Western energy ecosystem, even though Eastern national balances differ greatly one from another. All national balances may differ, but they have something in common: none of them is influenced by climate change mitigation. Nuclear energy has less to do with national climate morals and more to do with national needs.

On the *national level*, we identify 4 geographical country clusters that explain why the regional balances are in favour in the East and against in the West.

**The East** hosts 3 clusters: the Far Eastern small states (Japan, South Korea and Taiwan), the Asian emerging superpowers (China and India) and the former USSR states (Russia, Ukraine and Belarus). These 3 clusters summarise the East: they account for  $\approx 90\%$  of its reactors and net electrical capacity in operation and for  $\approx 80\%$  of its reactors and net electrical capacity under construction.

As for the **Far Eastern small states**, their national balances are *against* nuclear energy. Japan, South Korea and Taiwan are small, isolated states with large, foreign energy needs. They match 2 nuclear strengths (high energy density & stable fuel trade) and South Korea may match a third one (diminishing

overnight construction costs), but they all mismatch 1 acute weakness (safety after the Fukushima accident and safety in relation to North Korea). Accordingly, Taiwan will not further expand nuclear generation and will phase it out in 2025, South Korea will initially expand it and will phase it out in 2060 and Japan will gradually recover pre-Fukushima values but will delay a potential expansion.

As for the *Asian emerging superpowers*, their national balances are *in favour* of nuclear energy. China and India are huge countries with huge populations and emerging economies, where air pollution emerged too. Thus, China and India match nuclear's low human-health impact (low air pollution). Additionally, China matches 2 further nuclear strengths: its geostrategy (international nuclear exports as part of the OBOR initiative) and its profitability (even though cost was a potential weakness, it is a manifest strength in China, with its exemplary normalised construction times for domestic and international contractors).

Accordingly, both countries will likely drive worldwide nuclear expansion in the next years: India is building more and larger reactors, while China is building inside its borders more than 1/4 of the worldwide under-construction capacity and, beyond its borders, is exporting its domestic designs.

As for the *former USSR states*, their national balances are *in favour* of nuclear energy. The former USSR states are dominated by Russia, a worldwide energy giant, with extensive fossil fuel resources that are extensively exploited and traded. Its natural gas exports towards Europe traditionally transited via Ukraine and Belarus before reaching the European market, the stronghold of Russian energy exports. Russia controlled the loyalty of these transit countries by controlling their energy supply: evidently their natural gas consumption, but additionally their nuclear energy (since long in Ukraine, since recently in Belarus).

This is why Russian energy ecosystem matches 1 nuclear strength, geostrategy (boosting technology knowledge and exports). As Chinese nuclear policy is targeting mainly OBOR countries, the Russian one is targeting mainly its international allies in fossil fuel exports (additional examples are Turkey or several OPEC countries). Accordingly, although Russia has reduced its projections for domestic nuclear expansion, ROSATOM is "filling this gap" abroad and will compete with Chinese nuclear companies for the largest share of world nuclear exports.

**The West** hosts only 1 cluster: the Western long-standing leaders (the US, Canada, the UK, France and Germany). This single cluster summarises the West: it accounts for  $\approx 80\%$  of Western reactors and net electrical capacity in operation, its fleet is ageing (35 operational years on average) and has no generational replacement in sight (only 4 reactors under construction in these 5 countries, only 6 reactors under construction in the whole West).



As for the *Western long-standing leaders*, their national balances are *against* nuclear energy. The US, Canada, the UK, France and Germany are developed, industrialised democracies, where nuclear energy has invisible strengths and visible weaknesses. They may extend the life of operational reactors, but nuclear energy in the West will gradually wither.

On one side, Western nuclear energy is solving “invisible problems” with plenty of competition to solve them. As for environmental impacts, the Western long-standing leaders have less land footprint constraints (compared to the Far Eastern small states) and are rapidly deploying other low-GHG electricity sources. As for human-health impacts, their air pollution levels are very low (compared to Eastern and Southern Asia). As for grid security, they have abundant fossil-fuel capacity at least as dispatchable and as suitable for grid frequency control as nuclear energy. As for geostrategy, they will not increase nuclear exports as much as the Eastern counterparts (although the US values nuclear technological knowledge) and they already have some of the largest “renewable hedges” against trade fluctuations (although the UK and France value the “nuclear hedge”).

On the other side, Western nuclear energy is clashing with “visible problems” in a way unknown to any other energy species, most notably in Western Europe. As for cost, the “Goliath-like finances” of new reactors are mismatching the preferred “David-like finances”, operational reactors are threatened by growing competition of renewables and gas (mainly in the US, presumably in Germany and the UK) and shut down reactors are mired with financial uncertainty due to minimal decommissioning experience. As for safety and proliferation, the Western Europeans have lost touch with catastrophic events, hence fear them the most and hence fear nuclear accidents and nuclear weapons the most. As for waste, it is an uncertain problem worldwide that the Western confirmation bias perceives as more alarming.

In a nutshell, **nuclear energy will survive on the global stage, but is in the middle of its great migration.** Nuclear energy as energy species is migrating from the West towards the East: “nascent” reactors will be born in the East in higher number and with higher speed, “living” reactors are younger in the East and “deceased” reactors lived longer in the East. Nuclear energy will survive, but will fall short of IAEA’s and IEA’s most ambitious scenarios.

In the near future, nuclear energy will thrive in the Asian emerging superpowers (China and India) and, to a lesser extent, in the former USSR states (Russia, Ukraine and Belarus), whereas nuclear energy will gradually -and not immediately- wither in the Western long-standing leaders and the Far Eastern small states. Nuclear energy may well find new migratory destinations, mainly in the East, led by Chinese nuclear policy (targeting mainly “One Belt, One Road” countries) and Russian nuclear policy (targeting, among others, its international allies in fossil fuel exports).



Figure 3.29: Africa's Great Wildebeest Migration. In Africa, the wildebeest migrate periodically between the Serengeti National Park in Tanzania and the Maasai Mara National Reserve in Kenya. In the worldwide energy ecosystem, nuclear energy as energy species is migrating, without return, from the Western energy ecosystem towards the Eastern energy ecosystem (most notably to the Asian emerging superpowers and, to a lesser extent, to the former USSR states). Image from Abercrombie & Kent [Ken]

### 3.7 The nuclear species: evolutionary perspectives

*“Without an aggressive build-out of nuclear power, climate goals are still attainable, but at much greater expense” according to Jeffrey Sachs, the economist and director of the Sustainable Development Solutions Network, which co-leads the Deep Decarbonization effort. “The rest of the options are still feasible, but less attractive” he said. “We’d make a big mistake if we decide right now we don’t need it”.*

*Bloomberg*

*“Failing nuclear power is good for coal, bad for Earth”, [Ros17]*

So far we have analysed the *survival* perspectives of nuclear energy in the energy transition: the nuclear species will survive, but it is in the middle of its great migration and will fall short of IAEA’s and IEA’s most ambitious scenarios.

We would not worry about these perspectives if climate change was under control: if the nuclear species survived, fine; if it became extinct, fine too (Carl Sagan would say in this case: *“Extinction is the rule. Survival is the exception”*). However, climate change is indeed out of control: *“In fact, despite all our climate policies, global accords, solar advances, wind farms, hybrid cars and Teslas, greenhouse-gas emissions are still moving in the wrong direction. And as long as we’re emitting any at all, we’re only making the problem worse”* [Tem18].

Look at the big picture again: **“What is the real problem that we are facing?” Climate change**, arguably the most vital challenge that our generation faces. Climate change is *real*, because all five key climate change indicators are changing globally, although unevenly, and faster than before. Temperatures are rising, land and sea ice are melting, sea levels are rising, all triggered by rising atmospheric CO<sub>2</sub>. This climate change is *derived from human activity*, in particular from human GHG emissions, being CO<sub>2</sub> the most significant contributor. Human activity is the destabilising agent, which it is not all bad news: if we humans are the cause, we humans can as well become the solution. But do we really have reasons to care?

Is climate change such an alarming problem? Yes, climate change is an *alarming problem*. Global economic damages alone are shocking, but consider them together with the environmental, social and geopolitical impacts. Despite the fact that our predictions of the future are uncertain, our predictions reach overwhelmingly negative economic conclusions (global decreases of GDP, unevenly distributed) and leave other alarming questions open, such as the displacement and reduction of biodiversity, human migrations or violent conflict due to resource competition. These predictions are far from pleasing, but there is room for hope. If we humans have triggered the problem, can we humans put the means in place to solve it?

What can we do to alleviate climate change? **We need an energy transition.** The energy sector (lifecycle emissions of fuels, mainly combustion emissions) accounts for 2/3 of all human GHG emissions, being fossil fuels the most significant contributors: coal, oil and natural gas. Accordingly, the transformation of our energy sector, known as energy transition, is at the core of climate change mitigation. On one hand, it is a transition in *energy quantity* (accessible and efficient): some countries will consume less and some will consume more, while all should enhance energy efficiency. On the other hand, it is a transition in *energy quality* (clean, reliable, affordable): shift from fossil fuels towards cleaner energy sources and electrify final energy consumption.

We all seem to know what to do. **The *direction* for the energy transition is no longer the problem. The problem now is its *urgency*.** Christiana Figueres acknowledged that issue: “*The question for me is not the direction, but the speed and the scale [...] We need to be at the maximum of global emissions of GHG by 2020 [...] that sounds practically impossible [...] The question is: how are we going to make it achievable?*” [aD].

Why is the energy transition, our best solution to mitigate climate change, so clear in theory and so messy in practice? Because the smaller war of the energy transition inside the bigger war of climate change resembles the western film “**The Good, the Bad and the Ugly**”. In the energy transition, “the good” are the popular clean energy technologies (wind and solar energy, energy storage and electric vehicles), “the bad” are the fossil fuels and “the ugly” are the forgotten technologies (such as energy demand measures and nuclear energy). The good are united but underinvested, the bad are divided but overinvested, the ugly are largely forgotten and largely underinvested.

As in the Wild West, the good *alone* will not defeat the bad *in time*. McKinsey & Company shares this vision: “*Wind, solar and geothermal energy are growing rapidly, but the world will also continue to rely on fossil fuel for decades to come*” [NM16]. Unsurprisingly, big Oil & Gas companies share this vision too: “*Saudi Aramco and Royal Dutch Shell acknowledged that a shift towards renewable energy — including battery-powered cars — was under way but said oil and gas would remain indispensable for decades to come*” [War17b]. It seems that now, as in the Wild West, it is time to forge alliances. Maybe the good cannot win alone, but can win after all. Who could collaborate with the good?

Could the *bad* reach out to the good? Surprisingly yes, because the bad are internally divided and **Oil & Gas companies could become unexpected allies of the good.** Looking into the shorter term, Oil & Gas companies are *shifting from oil towards natural gas*, investing so heavily in LNG that its supply is on course to increase by 50% between 2014 and 2021. Meanwhile, lower fossil fuel prices and shorter-term contracts have endangered the commercial viability of this LNG surge.

As a consequence, Oil & Gas companies have immediately responded by *fighting coal* to make place for their gas, for example lobbying for carbon pricing mechanisms. Looking into the longer term, Oil & Gas companies will become “beyond-fossil energy companies”, *diversifying into green technologies*.

The bad are internally divided and Oil & Gas companies could, “sooner or later”, become unexpected allies of the good. The only problem here is that the “sooner or later” just mentioned has more to do with “later” than with “sooner”. **Oil & Gas giants, either state-owned or publicly-owned, need time to diversify.** The instability inside the OPEC countries serves as warning: if an energy transition away from fossil fuels unfolds too fast, these countries will lose their financial backbones and their geopolitical influence in the blink of an eye. The same applies at the corporate level: they are betting small on green technologies while investing big in oil and bigger in natural gas, which are still fossil fuels.

The bad need time to diversify and the energy transition cannot afford to give away more time: we know the direction, the problem now is the urgency. The good will surely appreciate this help of the bad, but that will not be enough.

Could the *ugly* reach out to the good? Unsurprisingly yes: an ideal solution for the energy transition is **1/3 renewables, 2/3 other green technologies**. The ugly are many (16 independent technologies, even some renewables) and diverse. Among them, the family of energy efficiency technologies, CCS and nuclear energy should ideally lead the way [IEA17d].

First comes *energy efficiency* (“reduced energy intensity”), which embraces most of the ugly. Global energy intensity has been decreasing for decades, has been the main driver flattening energy-related GHG emissions since 2014 and should ideally be the main driver reducing them in the near future. Despite progress hitherto, 2/3 of world energy use are not regulated by efficiency standards. The coverage is geographically uneven, led by China, and sectorally uneven, fostered by the industrial and residential sectors and stalled by freight transport. The public and the private sector are united, but the public sector initiative is lagging behind.

Second comes *CCS*, which should play an essential role if fossil fuels remain in electricity generation and industrial processes. Nonetheless, CCS is very visibly coming short of expectations. Its deployment will likely be negligible (global CCS in the 2020’s may only capture the yearly CO<sub>2</sub> emissions of Cuba and New Zealand) and, funnily enough, CCS is mostly dedicated to enhancing fossil fuel production. CCS capacity should expand tenfold to meet the 2DS targets for 2025 [IEA17d] and neither the private sector nor the public sector are closing the gap. The failure in Kemper County is the most visible symptom of the decreasing R&D public investment in CCS over the last few years in IEA member countries.



Third comes *nuclear energy* and we already know its survival perspectives. Nuclear energy will survive on the global stage, but is migrating from the West towards the East: “nascent” reactors will be born in the East in higher number and with higher speed, “living” reactors are younger in the East and “deceased” reactors lived longer in the East. Nuclear energy will survive, but will fall short of IAEA’s and IEA’s most ambitious scenarios.

In essence, no one is performing as we would like to: the good will not defeat the bad *in time*, while some of the bad -namely, Oil & Gas companies- may help but *need time* to diversify and all of the ugly are *underperforming*. This energy transition has a clear direction in theory, but is upside down in practice. This means climate change mitigation is upside down in practice, still out of control. Bad news. Bad news that warn us in time: we must **urgently redesign the energy transition and its implementation**.

Will the nuclear species have better perspectives in a redesigned, ever-changing energy transition? We believe it could and we believe it should, because nuclear species has some of the lowest lifecycle CO<sub>2</sub>-equivalent emissions per electrical MWh [TBA13]. Nowadays, this potential strength does not manifest in any national balance: nuclear energy has less to do with national climate morals and more to do with national needs. Will this potential strength manifest in the near future? Maybe, but we believe that this manifest strength, on its own, will not boost nuclear energy.

How should nuclear energy (and the energy ecosystem) *evolve* then? Let’s recap our conceptual framework: twenty-two energy species share one energy ecosystem that is shaped by six stakeholders. The energy ecosystem as a whole can evolve out of endogenous changes and exogenous changes.

On one hand, endogenous changes come from the energy development companies: the internal “shaping agents”, the genes of the nuclear species that express themselves in certain internal technological features. On the other hand, the exogenous changes come from the energy-ecosystem stakeholders: the 6 external “shaping agents”, the environmental conditions to which the nuclear species should better adapt. They are energy management companies, large energy users, the financial sector, policy-makers, international organisations and the civil society. Ideally, we need an **ecosystem-wide evolution, where endogenous and exogenous changes converge for nuclear energy**.

How should this ecosystem-wide evolution look like? This master thesis does not provide an elaborate, justified answer to that question. Nonetheless, this master thesis does provide the starting point for the answer, because now we understand better why the possible and the actual are so far apart for nuclear energy. **Now we know the real problems, now we can design effective solutions. The second part is what lies ahead for future research.**

How does our *intuition* imagine this ecosystem-wide evolution? It imagines different evolutions in the East and West: growth in the East and healing in the West. As Alan Turing would say: “*We can only see a short distance ahead, but we can see plenty there that needs to be done*”.

Our intuition imagines **growth in the East, “the gold mine for new construction”**. As for the Far Eastern small states, KEPCO may well play important domestic and international roles. First, KEPCO may expand domestically if the relations with North Korea continue the initial 2018’s improvement [HM18b] & [HM18a] & [HM18c] & [JA18]. In the words of Moon Jae-In, South Korea’s president: “*The dialogue between South Korea and North Korea has begun. We plan to turn this dialogue into a chance to improve South-North Korea relations and also resolve the North Korean nuclear issue through dialogue*” [HM18c]. This smoothed relations with North Korea could also benefit Japanese nuclear recovery and Taiwanese nuclear preservation. Second, KEPCO should may expand internationally: first in the East, if it successfully finishes the 4 APR1400 under construction in the UAE [Car17], and then in the West, starting in the UK [WJA17].

Despite KEPCO’s contribution to growth, the largest growth will come from the Asian emerging superpowers with the contributions of both domestic and foreign contractors. The better performance of AREVA’s EPR in China should motivate the arrival of more Western contractors so that they “get back in shape”.

Moreover, Chinese and Russian contractors should lead the way in nuclear exports: the Chinese nuclear policy targeting mainly OBOR countries and the Russian one targeting mainly its international allies in fossil fuel exports. In order of “geopolitical convenience” for the West, first comes KEPCO, second come the Chinese contractors and third comes ROSATOM. The future success of Chinese contractors at Bradwell B, in the UK, may increase the Western trust on them [Vau17a].

Our intuition imagines also **healing in the West, “the gold mine for life extensions and decommissioning”**. We cannot imagine a nuclear expansion in the West only because their nuclear contractors got back in shape. Improving the “Goliath-like” finances of *new* reactors would also help, for example by looking for more distributed investment sources [WP18] & [War18] or by “shared projects” led by South Korean or Chinese contractors. Experimental technologies, such as Generation IV Reactors or Small Modular Reactors, may help in the long term. However, all of that would solve only *partially* the cost mismatch of Western nuclear energy: why would the West build new reactors if operational and shut down ones are under financial uncertainty?

We could improve the economics of *operational* reactors with carbon taxes, although carbon taxes cannot be an answer to everything [TdPM17] & [But17h]. Bloomberg New Energy Finance also highlights that capacity payments or capacity

markets (to guarantee the reliability of the grid) cannot be an answer to everything [Che17]. Combining these or other measures, and once operational economics improved, life extensions in the West would expand, but would have to streamline the relicensing protocols (a license renewal in the US takes typically  $\approx 30$  months [NRC13]).

We may alleviate the financial threat of *shut down* reactors with coordinated, international research and action. As European countries created an European consortium (Airbus Industrie) to rescue their aeronautical industry, they could also create an European consortium (a redesign of the current Euratom) to deal with nuclear decommissioning and waste more effectively [But17d] & [AW] & [Coma].

Once the overall nuclear economics improved, the environmental awareness in the West could play a role. “How” to raise the environmental awareness of the energy stakeholders is an open question right now. The “why” part is clearer, at least for the nuclear species. Most evidently, the low GHG emissions of nuclear energy would become a manifest strength and, less evidently, climate change would become a more threatening catastrophe than nuclear accidents or nuclear weapons. If the fear of climate change challenges the fear of nuclear catastrophes, the waste and proliferation of nuclear energy would become less visible in comparison.

If we add up all these advances, we imagine an evolved energy species matching better with an evolved energy ecosystem. Only then our *intuition* imagines that nuclear energy would look, worldwide, less like a problem and more like a solution, at least as **partial and transitory solution to climate change**.

*Progress means getting nearer to the place you want to be. And if you have taken a wrong turning, then to go forward does not get you any nearer. If you are on the wrong road, progress means doing an about-turn and walking back to the right road; and in that case the man who turns back soonest is the most progressive man.*

*C.S. Lewis*

*“Mere Christianity”*



# Chapter 4

## A call for hope and responsibility

### ON THE INDIVIDUAL LEVEL

*At the same time, Bartholomew has drawn attention to the ethical and spiritual roots of environmental problems, which require that we look for solutions not only in technology but in a change of humanity; otherwise we would be dealing merely with symptoms. He asks us to replace consumption with sacrifice, greed with generosity, wastefulness with a spirit of sharing, an asceticism which “entails learning to give, and not simply to give up. It is a way of loving, of moving gradually away from what I want to what God’s world needs. It is liberation from fear, greed and compulsion”.*

*Pope Francis*

*“Encyclical letter Laudato Si’ of the Holy Father Francis on care for our common home”, [Fra15]*

*With over 50% of the world’s population under the age of 30, it is of concern that young people perceive decision-makers as not listening to them before decisions are made. By its sheer size, the current youth generation is already influential. And that influence is set to grow as they come to occupy a larger proportion of the workforce and voter base, as they become employers and as their consumer spending grows.*

*[...]*

*Climate change and the environment remain the top global concerns revealed in this survey [of people aged 18 to 35] for the third year in a row [...] [In this survey] young people state whether they are willing to change their lifestyles to protect the environment: to avoid any suspense, the answer is a resounding “yes” and is one of the strongest results in this year’s survey.*

*World Economic Forum*

*“Global Shapers Survey 2017”, [For17]*

## ON THE INTERNATIONAL LEVEL

*We know that technology based on the use of highly polluting fossil fuels – especially coal, but also oil and, to a lesser degree, gas – needs to be progressively replaced without delay. Until greater progress is made in developing widely accessible sources of renewable energy, it is legitimate to choose the less harmful alternative or to find short-term solutions.*

*[...]*

*In recent decades, environmental issues have given rise to considerable public debate and have elicited a variety of committed and generous civic responses. Politics and business have been slow to react in a way commensurate with the urgency of the challenges facing our world. Although the post-industrial period may well be remembered as one of the most irresponsible in history, nonetheless there is reason to hope that humanity at the dawn of the twenty-first century will be remembered for having generously shouldered its grave responsibilities.*

*Pope Francis*

*“Encyclical letter Laudato Si’ of the Holy Father Francis on care for our common home”,  
[Fra15]*

Frodo: *“I can’t do this, Sam.”*

Sam: *“I know. It’s all wrong. By rights we shouldn’t even be here. But we are.*

*It’s like in the great stories, Mr. Frodo. The ones that really mattered. Full of darkness and danger they were. And sometimes you didn’t want to know the end. Because how could the end be happy? How could the world go back to the way it was when so much bad had happened?*

*But in the end, it’s only a passing thing, this shadow. Even darkness must pass. A new day will come. And when the sun shines it will shine out the clearer. Those were the stories that stayed with you. That meant something. Even if you were too small to understand why.*

*But I think, Mr. Frodo, I do understand. I know now. Folk in those stories had lots of chances of turning back only they didn’t. They kept going. Because they were holding on to something.”*

Frodo: *“What are we holding on to, Sam?”*

Sam: *“That there’s some good in this world, Mr. Frodo. And it’s worth fighting for.”*

*J.R.R. Tolkien*

*“The Lord of the Rings: The Two Towers”, film adaption*





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