A seismograph for measuring the transformation to net zero greenhouse gas emissions – discussion paper

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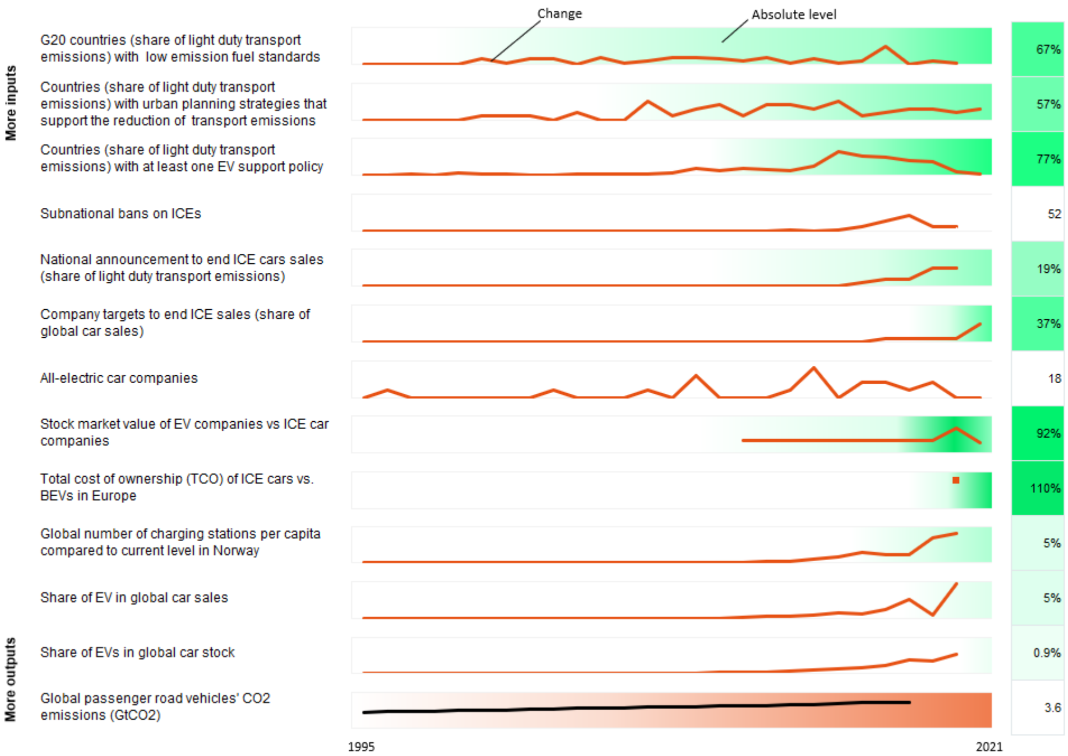
Abstract

This discussion paper sketches the idea of a "transformation seismograph" to detect the signs and measure the speed and magnitude of transformation to net-zero greenhouse gas emissions before it is seen in greenhouse gas emissions projections. We show that some factors, that make a low carbon transformation more likely before it is seen projections of greenhouse gas emissions, are measurable. We tested the concept to measure progress in electricity generation and electric light-duty vehicles. We propose to set up a comprehensive monitoring system with a variety of indicators per sector to measure if a transformation is likely to happen. Such information would help policy makers to design interventions and international cooperation to support the transformation most effectively.



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1 Introduction

The transformation to a zero-carbon economy by the middle of the 21st century becomes increasingly visible now. Changes take place at various levels: from the small experimental level to meso-scale efforts involving multiple sectors such as energy, mobility, agriculture, diet and nutrition, human settlements, industry and the land sector leading to system-wide changes. Here, 'transformation' means a fundamental, multi-dimensional change of the sociotechnical system (Geels et al., 2017; Hölscher et al., 2018).

Models that generate and estimate greenhouse gas emission trajectories based on current policies may not always represent the pace of changes on the ground, with high chances that they are falling behind real developments and not providing a correct depiction of future system-wide transformation. An example is the representation of expansion of renewable power generation by the International Energy Agency, that are underestimated year on year (Boehm et al., 2021).

A single metric of declining greenhouse gas emissions, while the desired and necessary outcome, is not always sufficient to track the process of system-wide and long-term transformation, which emerges at varying speed, intensity and scale from multiple dimensions (Höhne et al., 2020).

The system transformation is so vitally important for solving the issue of climate change, so we ask in this discussion paper: How can the transformation be measured before it is visible in greenhouse gas emissions? Such information would help stakeholders to concentrate efforts on areas where the transformation is lagging and to remove most relevant barriers.

The transformation can occur in an "s-shape" in which change is seemingly impossible at first or associated to very high level of uncertainty of success, then ratchets up quickly, to attain a new stabilized state in the future. The idea of sector transformation, breakthroughs and s-curve shaped transitions in the past and potentially in the future has been covered by a series of reports (Boehm et al., 2021; Climate Action Tracker, 2019; Falk et al., 2020; Global Challenges Foundation, 2021; Grubb et al., 2020; Race to Zero, 2021; Roy et al., 2021; Systemiq, 2020a; World Economic Forum, 2019), the report on net zero by the IEA (IEA, 2021c) and various scientific publications (Child & Breyer, 2017; de Haan & Rotmans, 2018; Geels, 2002). Some also note that exponential change is not evident across all sectoral transformations (e.g., forest restoration or food loss and waste) (Boehm et al., 2021).

The transformation process can be categorised in phases; we describe here the potential phases of technology deployment, cognisant that the transition has more societal dimensions (Geels et al., 2017). It may start with multiple fragmented innovations (initiation stage in Figure 1). In the second phase, learning, reinvestment, growing technical knowledge give rise to many intermediary actors and new social routines, practices through new technology adoption start emerging but still do not become the new norm. A third phase is initiated by reaching a tipping point or transformation point after which the system can transform at exponential speed. In the fourth phase new systems become institutionalised. Change is not automatically guaranteed. At any point the system may revert to the status quo or stays stagnant. In all stages, the transition can be supported by enabling conditions ('effort' in Figure 1).

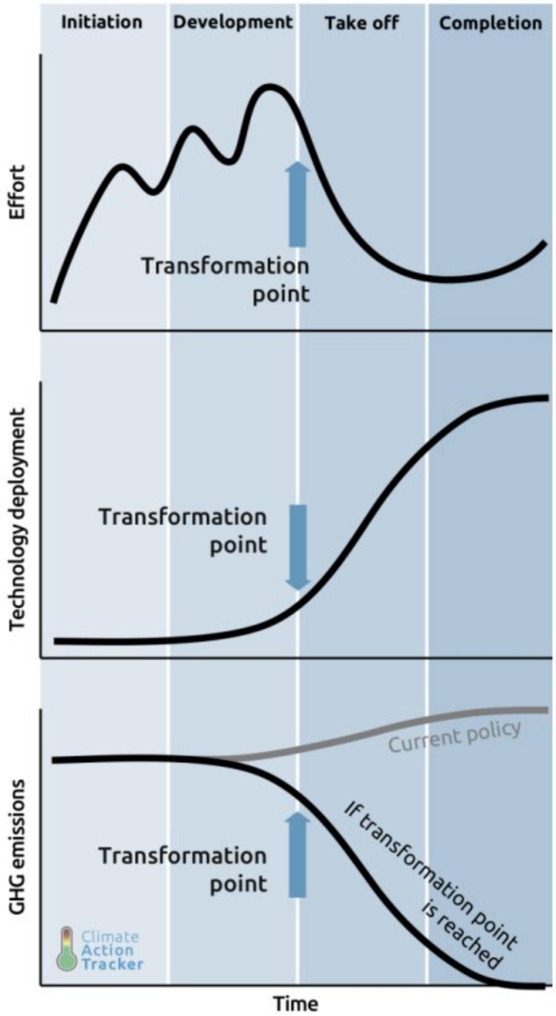

Figure 1. Concept of a system change which proceeds via 4 stages, including a "transformation point' where a noticeable change occurs and indicators measuring that transition (Source: Climate Action Tracker, 2019)

To understand the state of the transformation, it can be helpful to track indicators across systems and scales. Such indicators can also measure the underlying enabling conditions, i.e., the factors that make the transformation possible.

This discussion paper presents a first illustration how to track transformation. It is meant as initial input to the discussion not yet being comprehensive. With this main goal, section 2 presents how to measure conditions that enable transition. Section 3 presents some illustrative examples to demonstrate how to track the transformation. Section 4 provides some conclusions.

2 How to measure the transformation

Past literature has identified conditions that enable and support systemic and transformative change. Most recently the IPCC 1.5°C special report (IPCC, 2018) categorised them into "multilevel governance", "institutional capacity", "policy instruments and finance", "technological innovation and transfer" and "changes in human behaviour and lifestyles." Other reports (Boehm et al., 2021; Falk et al., 2020; Geels F, 2002; Systemiq, 2020b) organise these enablers differently and / or add new elements (see left of Figure 2).

A comprehensive framework to systematically track progress towards transformation is much less researched compared to enabling factors. There are many indicators to track progress towards transformation (Boehm et al., 2021; UNFCCC, 2021). A log frame model for tracking subnational and non-state climate action was proposed by Hale et al. (2021), which distinguishes indicators related to 'inputs' from 'outputs', 'outcomes' and 'impact'. Indicators can be defined to identify early signs of a transformation, usually inputs, or more the results of the transformation, here outputs. These indicators do not only measure the transition but may also support the analysis of trends in different enabling factors (Figure 2).

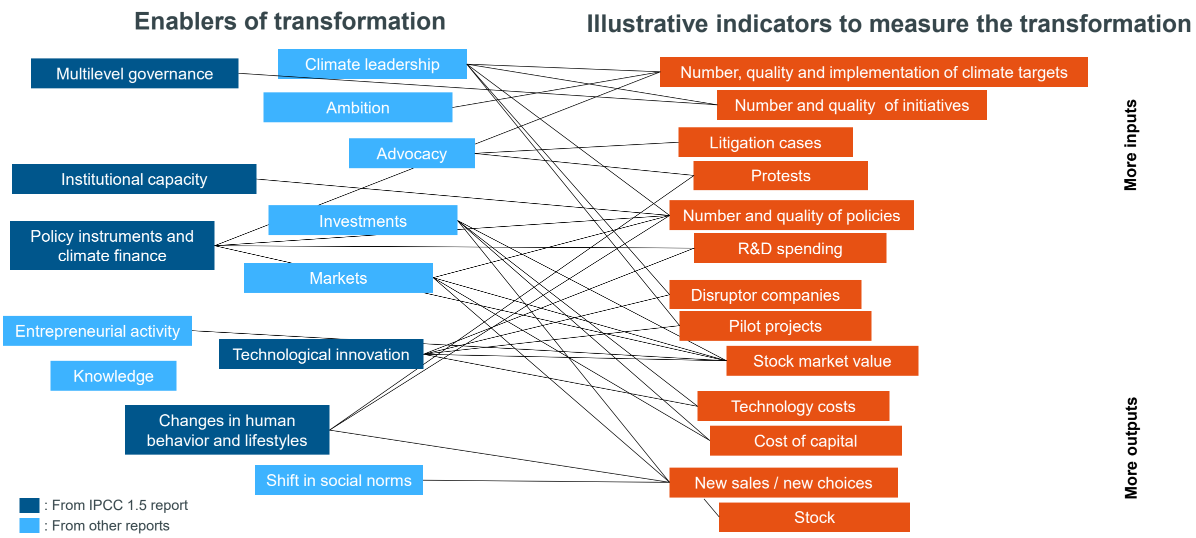

Figure 2. Illustrative overview of enablers of the transition (some of which are overlapping) and how to measure them (collected from Boehm et al., 2021; Climate Action Tracker, 2019; Falk et al., 2020; Global Challenges Foundation, 2021; Grubb et al., 2020; IPCC, 2018; Race to Zero, 2021; Roy et al., 2021; Systemiq, 2020a; World Economic Forum, 2019)

We draw some generic insights from analysing indicators to measure transformational change:

- **One indicator can indicate the presence of various enablers.** For example, the number of companies that sell a potentially disruptive technology can be an indicator for climate leadership and at the same time for technological innovation.
- **Input indicators can detect change earlier than output indicators:** An effect on 'output' indicators, such as share of new sales or sectoral emissions, is only observed once many other developments have already taken place. To track 'input' indicators, such as number of targets or policies, or 'intermediary' indicators, such as number of companies for a particular technology, provide early signs that a transformation is under way.
- **Evidence of change in 'input' indicators increases likelihood of transformation, but does not guarantee it.** For example, the number of net zero commitments/pledges has skyrocketed in 2020/2021. These are examples of growing deeper and political support, but could potentially be meaningless if not followed up by ready action to achieve these targets. Seeing some change in some indicators is a necessary, but not sufficient indication of a transformation.
- **Capturing early signs of the transformation will require multiple indicators and some will be sector-specific:** Many enabling factors must interplay to initiate the transformation. The transition therefore must be measures using a variety of indicators. There is also no one-size-fits-all- solution on how to incentivise the transition and approaches and cause effect chains

will vary from sector to sector. Therefore, also the selection of indicators to measure the transition must vary.

- **Detecting exponential change requires special attention:** Since the exponential change could happen very rapidly from very low levels, measurement needs to be precise and timely. Measuring the first or second derivative of an indicator may provide early warning signals. Real time data would be ideal, as a time lag of one to two years to get data for an indicator would be insufficient. Methodologies for doing so are still evolving (Boehm et al., 2021).

3 Transformation seismograph

This section sketches out the idea of a "transformation seismograph". A "transformation seismograph" can give an early warning signal with small perturbations at the beginning, later some elements of the system start shaking, later strong vibrations occur in all areas of the system until tipping or transformation point (point of no return) is reached.

Given the insights from the analysis above, we collect illustrative example indicators (only indicative and not within a framework and not comprehensive) to measure nascent transformation. Indicators are sorted from input to output indicators. We test the concept here for the topics of renewables and electric light duty vehicles because these areas show already signs of transformation and data availability is good. We focus for these examples at the technology innovation, knowing that full measurement of the transformation would have to take other societal factors into account. If global data was not available, regional data was used to illustrate the indicator.

For each indicator we measure the absolute level and the change (first derivative) to be more sensitive (Figure 3). The annual change is shown as line for the years where data is available. The absolute level is indicated by the shading of the background. That absolute level is, where possible, put in context with what would constitute the level needed for this indicator (100% = dark green). The last available value is provided on the far right. In this example, 100% indicates that all G20 countries have policies in place to support renewables. This framework does not yet provide information if the overall transformation is fast enough for the temperature limit of the Paris Agreement.

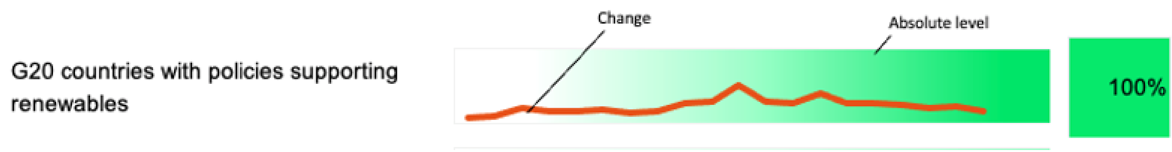

Figure 3: Example of an indicator in the transition seismograph

3.1 Electricity generation (renewable and coal phase out)

Several recent changes in indicators suggest that the transformation to renewable electricity is approaching a transformation point (Figure 4). Renewable costs reductions have been surpassing expectations year after year, net capacity additions of renewables have overtaken conventional technologies already in 2012 and today are the new normal (80% of capacity additions in 2020). The notion to move to 100% renewable electricity is getting traction with such national targets covering 3% of electricity emissions and with wider spread and increasing number of city /regional 100% renewable targets. Risk premiums on cost of capital have decreased to zero in some jurisdictions. In addition, investors turn away from coal, oil and gas. Major emitting economies have set dates to phase *out coal in their electricity mix. Even though the effect of these actions might not be strongly observed in emissions to date, their effect is visible in the indicators.*

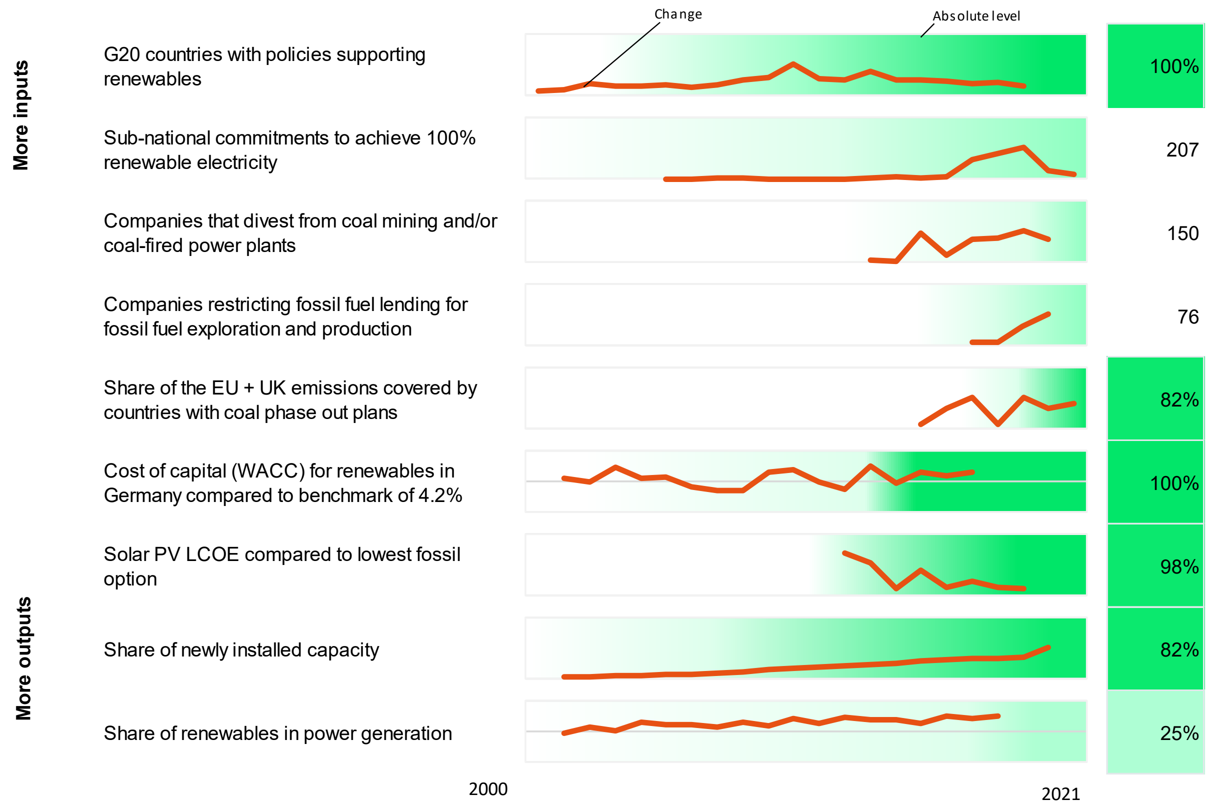

Figure 4 Renewable transformation seismograph. Annual change shown for the years where data is available. Absolute level is shown only indicatively and is normalised to what would constitute the level needed for this indicator. Where normalisation is not available, the absolute level is given in the last column.

The electricity generation sector remains the largest sectoral emissions source. Emissions in this sector continued to *increase* in the past twenty years, despite all positive developments. However, the yearly rate of increase in emissions has dropped from 3.2% between 2000 and 2010 to 1.4% since (Lamb et al., 2021). This slowdown is a positive development but remains insufficient to close the emissions gap.

A transformation in the electricity sector to zero greenhouse gas emissions is fundamental to meet the temperature goals of the Paris Agreement. It would have spill over effects to all other energy demand sectors, that will become increasingly electrified in the next decades (see Electric light-duty vehicles below). The higher levels of activity in the past years indicate a transformation is under way, even though deep emissions reductions do not show in output indicators, such as the share of renewable electricity generated or electricity-related emissions.

Policy support for renewable electricity is widespread, especially is major emitting economies. In the past twenty years, countries have implemented a diverse set of policy instrument types to remove barriers and directly support the uptake of renewable energy technologies, such as feed-in-tariffs, subsidies and renewable energy targets (Nascimento et al., 2021). Since 2010, all G20 countries have at least one policy to support renewables in electricity generation (Fekete et al., 2021). However, an increase in the number of policies needs to be supported by robust implementation plans, and in several cases, higher ambition.

Renewable electricity targets have become prevalent in most countries in the world. Already in 2017, 87% of the countries had executive or legislative targets in force (Iacobuta et al., 2018). However, the number of countries that aim to increase renewable electricity to 100% is still low and cover only 3% of global emissions (REN21, 2021). Subnational jurisdictions move faster in some cases. In the United States, over 200 counties, cities and states have implemented ambitious renewable targets of 100% electricity as of 2020 (Sierra Club, 2021).

More recently, a sharper movement away from fossil fuels have started. This adds uncertainty to investments related to fossil fuels and improve the overall outlook for renewables. Every year, more investors and insurers rethink fossil energy investments. Since 2013, at least 150 of them have introduced measures to divest from coal mining and/or coal-fired power plants (IEEFA, 2021b). Since 2017, 76 banks and investors have restricted fossil fuel lending to oil and gas exploration and production (IEEFA, 2021a). The UK has committed to stop funding fossil fuel projects abroad in the future, covering "export finance, aid funding and trade promotion for new crude oil, natural gas or thermal coal projects" (Prime Minister's Office, 2020).

An increasing number of countries have adopted coal phase-out plans. The Powering Past Coal Alliance is an initiative that includes 41 national governments and aims to remove unabated coal-fired power generation from the electricity mix. In the European Union + UK, some more concrete measures have been taken and 17 countries – covering over 80% of the block's emissions – have adopted a limit date to remove coal from their electricity mix (Europe Beyond Coal, 2021).

A reduction in costs of capital indicates lower risk premium associated with renewable investments and reduce overall renewable electricity costs. The weighted average cost of capital (WACC) is a common metric to measure how difficult it is to raise funds for projects in distinct countries, but national data is scarce (Ameli et al., 2021). In Germany, for example, costs of capital is no longer an issue; the average renewable WACC was approximately 6.8% in 2000 and already reached 1.8% in 2017 (Steffen, 2020). These current values are already lower than expectations under cost-optimal 2°C compatible scenarios of 4.2% (Ameli et al., 2021). WACC values are still considerably higher in developing countries and emerging economies, which require further policy intervention to drive down overall finance costs (Grubb et al., 2020).

Changes in capacity additions are observed much earlier than in share of total power generation. Renewable electricity yearly installed capacity surpassed non-RE technologies already back in 2012. In 2020, new capacity was almost only from renewables; the share of new renewable capacity additions over total capacity additions surpassed 80%. Several major economies drive this group. India, for example, is expected to be the main contributor to renewables capacity expansion in 2021, with annual additions doubling from 2020 (IEA, 2020).

These developments help laying the foundation to a transformation away from fossil fuels. This can be measured in the share of renewables in the total power generation. This metric has been consistently increasing since 2008 but has only increased from approximately 19% to 25% in a period of ten years. Some examples show that a faster national transformation is possible. Among the G20 economies, the UK and Germany show the highest renewable electricity percentage point increase between 2010 and 2020, 25 percentage points in Germany and 26 percentage points in the UK (Jones et al., 2020).

3.2 Electric light-duty vehicles

The transformation from internal combustion to full battery electric light-duty vehicles is progressing faster than expected (Figure 5). Light-duty electric vehicles (EVs) are already commercial in several countries where there are signs that the transformation is past the transformation point, e.g. Norway. Global markets are changing: Electric car companies together are worth more than conventional car makers together. A third of global car production is from companies that plan to phase out internal combustion engines in the next years. However, transformation is not yet global. Challenges include high upfront investment costs for those vehicles in some jurisdictions and low range autonomy compared internal combustion engine (ICE) vehicles and the lack of charging infrastructure and sustainable production.

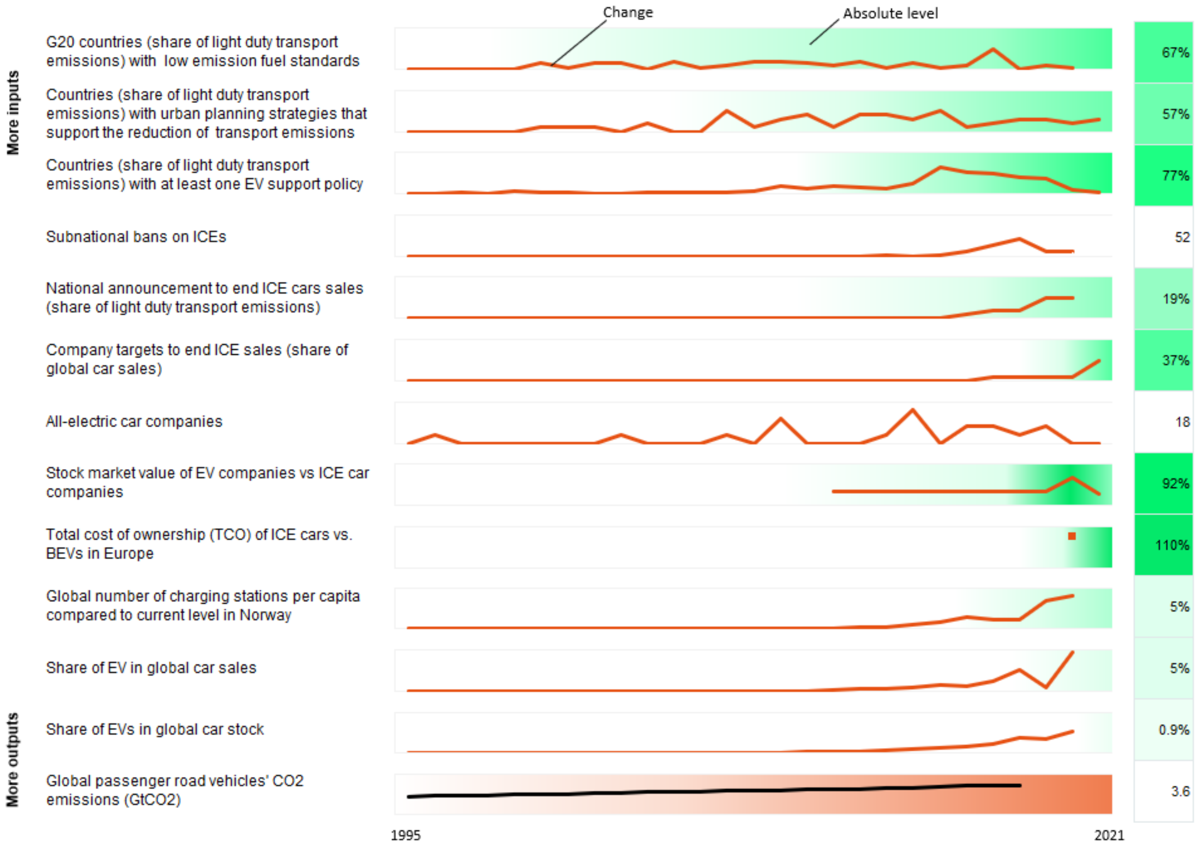

Figure 5. illustrative indicators measuring the nascent transformation *towards electric light duty vehicles*

Government activity to support electric light-duty vehicles has increased significantly in the last decade. Many governments started with fuel economy standards for new cars, which by now are applied in almost all countries (Nascimento et al., 2021). Policies that support EVs have been almost absent five years ago but are now found today in 33 countries, covering 77% of global road transport emissions (Lamb et al., 2021).

However, new governance institutions are needed for the complex system transformation involving transport, power and land use planning according to each city characteristics including micro-mobility (e-bikes, e-scooters, e-autorickshaws), electric cars, electric buses (including trackless trams) and the many lighter versions of freight delivery vehicles, all of which work better in certain parts of cities and regions than others. Urban planning strategies that support the reduction of road transport emissions are currently present in only 27 countries, covering only 57% of road transport emissions (Lamb et al., 2021; Nascimento et al., 2021).

The aim for a 100% transformation to zero emission cars has manifested itself in a variety of new targets by a variety of actors in recent years. Many cities and regions plan to ban internal combustion engines; for example, New York State, Amsterdam, Athens, Madrid, Mexico City, New York State and Paris (Harvey, 2016; New York State, 2021; Reuters Staff, 2019). In addition, 15 countries, covering 19% of light duty transport emissions, made similar announcement (IEA, 2021b; Lamb et al., 2021). Nine conventional car companies have targets to end the sales of ICE, together covering 37% of the 2017 global car production (International Organization of Motor Vehicle Manufacturers, 2018; Lekach, 2021).

Global stock markets are starting to invest in electric vehicles rather than in internal combustion engines. For example, the number of new start-up companies producing only electric vehicles increased to at least 15, most of them founded in the last 10 years.[1] The total stock market value of companies producing only EVs (driven by Tesla) was higher than the stock market value of all other major car makers together in 2020 (Market Cap, 2021). This may flip back again in 2021 with conventional car companies catching up and committing to higher shares of EVs in their production.

The total cost of ownership (TCO) of EVs has decreased substantially in the last years and is for several types now lower than the TCO of conventional ICE cars in several economies. This decrease in cost is projected to continue in the next ten years, making EVs increasingly competitive with or outperforming ICE cars when looking at initial investment and operational costs (ElementEnergy, 2021; Harto, 2020). However, initial investment is still significantly higher for EVs than for ICEs.

The provision of charging infrastructure is a challenge for most of the cities. Leading is Norway with 3 charging stations per one thousand inhabitants, Europe 0.8 and globally 0.2 (IEA, 2021a).

Supply of critical minerals is a potential constraint, future demand is larger than availability, even after changes in the EV´s technology have been applied (Månberger & Stenqvist, 2018). Some battery materials are critical due to their economic or national security importance or high risk of supply disruption (UK Government, 2019). Many of the materials are rare earth elements (REEs). The critical minerals identified by most nations are: Neodymium and Dysprosium for permanent magnets in wind turbines and electric motors; Lithium and Cobalt, primarily for batteries though many other metals are involved and, Cadmium, Telluriam, Selenium, Gallium and Indium for solar PV manufacture (Giurco et al., 2019). Predictions are that the transformation to a clean energy world will be significantly energy intensive putting pressure on the supply chain for many of the metals and materials required. Recycling must be enhanced to reduce the pressure on those natural resources.

Despite the challenges, new sales of plug-in cars reached a record high of 85% in Norway (June 2021), while they are globally still at roughly 4% (IEA, 2021a). If Europe (2020 at 10%) would follow the same exponential trend as Norway, it would be at 85% already by 2027. However, the global car stock is still dominated by internal combustion engines (16% electric in Norway and below 1% globally) and change in emissions from passenger transport is not yet visible (IEA, 2021a).

[1] These include, for example, Aiways, Bollinger, Byton, Faraday Future, Fisker, HiPhi, Kandi, Lucid, Nio, Polestar, Rimac, Rivian, Seres, Tesla and Xpeng

4 Conclusions

This discussion paper illustrates how we can measure early signs that a low-carbon transformation with a 'transformation seismograph'.

Input indicators indicate change earlier than output indicators. To track 'input' indicators, such as number of targets or policies, or 'intermediary' indicators, such as number of companies for a particular technology, provide early signs that a transformation is under way.

Measuring change in indicators shows that there is action on the ground, which indicates a higher likelihood of a transformation, but does ensure it will take place. These are examples of growing support but could potentially be meaningless if not followed up by action realise this potential.

The measurement of the transformation can only be successful when using many indicators and sector specific indicators. Many enabling factors must interplay to initiate the transformation.

Attempting to detect exponential change requires special attention. Since the exponential change would happen very rapidly from very low levels, measurement needs to be precise and timely.

Applying this approach illustratively for example areas we find:

- **Electricity generation:** Several recent changes in indicators suggest that the transformation to renewable electricity is approaching a transformation point. Renewable costs reductions have been surpassing expectations year after year, net capacity additions of renewables have overtaken conventional technologies already in 2012 and today are the new normal (80% of capacity additions in 2020). The notion to move to 100% renewable electricity is getting traction with such national targets covering 3% of electricity emissions and with wider spread and increasing number of city /regional 100% renewable targets. Risk premiums on cost of capital have decreased to zero in some jurisdictions. In addition, investors turn away from coal, oil and gas. Major emitting economies have set dates to phase out coal in their electricity mix. Even though the effect of these actions might not be strongly observed in emissions to date, their effect is visible in the indicators.
- **Electric light duty vehicles:** The transformation from internal combustion to full battery electric light-duty vehicles is progressing faster than expected. Light-duty electric vehicles (EVs) are already commercial in several countries where there are signs that the transformation is past the transformation point, e.g. Norway. Global markets are changing: Electric car companies together are worth more than conventional car makers together. A third of global car production is from companies that plan to phase out internal combustion engines in the next years. However, transformation is not yet global. Challenges include high upfront investment costs for those vehicles in some jurisdictions and low range autonomy compared internal combustion engine (ICE) vehicles and the lack of charging infrastructure and sustainable production.

We did not evaluate if the changes are fast enough for the goals of the Paris Agreement. Others find that both renewables and electric vehicle expansion is still off track (Boehm et al., 2021).

We propose here to set up a comprehensive monitoring system with a variety of indicators per sector to measure if a transformation is likely to happen. Such information would help policy makers to design interventions and international cooperation to support the transformation most effectively.

We suggest the following next steps

- **Research on drivers of change:** further research is needed on the drivers of change at each stage of the transformation for all of these sectors. This will inform the indicator selection.
- **Set up indicator system:** this initial illustration has shown that collecting a larger set of indicators from input to output per sector can give valuable information of the progress of the transformation. A comprehensive indicator system is critical to track the transformation. In the ideal case it would be a real time tracking. Individual initiatives such as the Systems Change Lab will be showcasing data for both output and input related indicators for about 40-50 transformations spanning several sectors, and the UNEP emissions gap report could synthesise research from various initiatives.
- **Increase data availability:** the work has revealed many data gaps for fundamental indicators. We would suggest that the international community collaborated to fill these data gaps, including innovative approaches, such as data science with a view to provide real time data.
- **Use information in current policy scenarios:** the examples showed that transformations are faster than expected (at least in some areas). These developments are not yet included in current policy projections. We would suggest that efforts are made it include this up-to-date information.

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