Towards a sustainable global energy supply system

Rodrigo Guzman, atmospheric physicist

Outline

1) A simple framework to identify key human-environment interaction mechanisms

2) Global electricity supply systems : limits of the existing technologies to head towards and effectively achieve full sustainability

3) A game-changing power supply infrastructure : The Light Tower of Babel (LTB)

4) XXI century progressive deployment of this new infrastructure : a possible pathway, a desirable target

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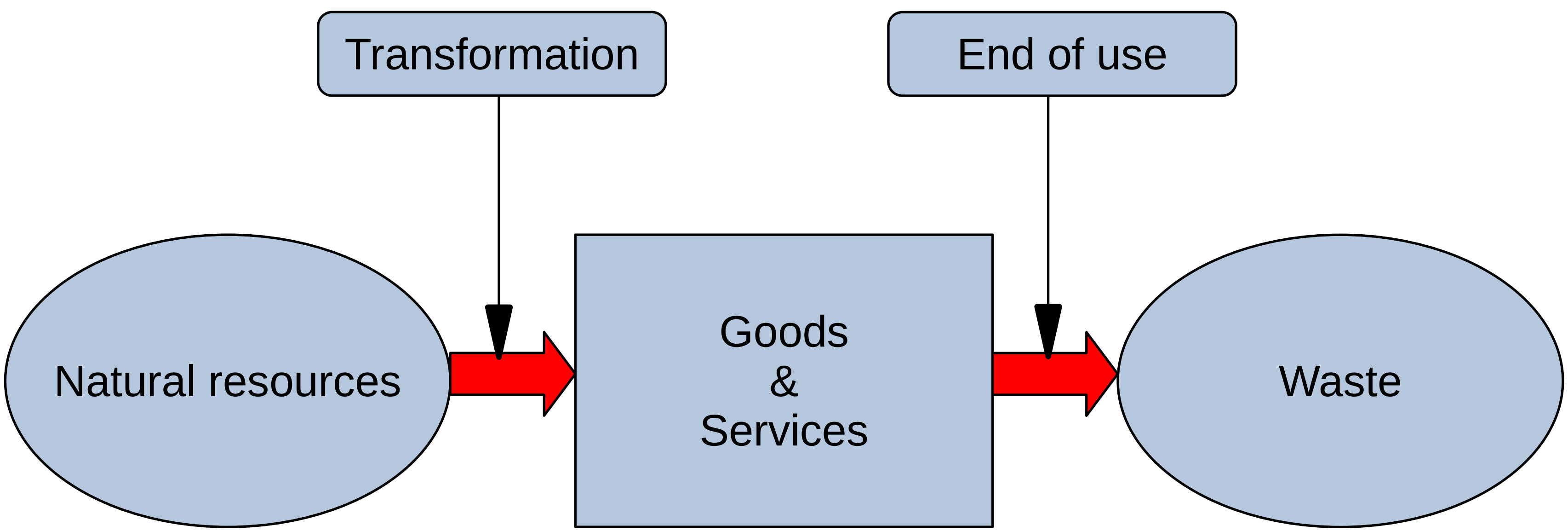
Key human-environment interaction mechanisms

One of the simplest diagram we can start from concerning human-environment interactions is the one below. In order to produce and benefit from all what humans can provide to themselves, they need to transform natural resources in goods and services which, once used, may produce waste released in the environment.

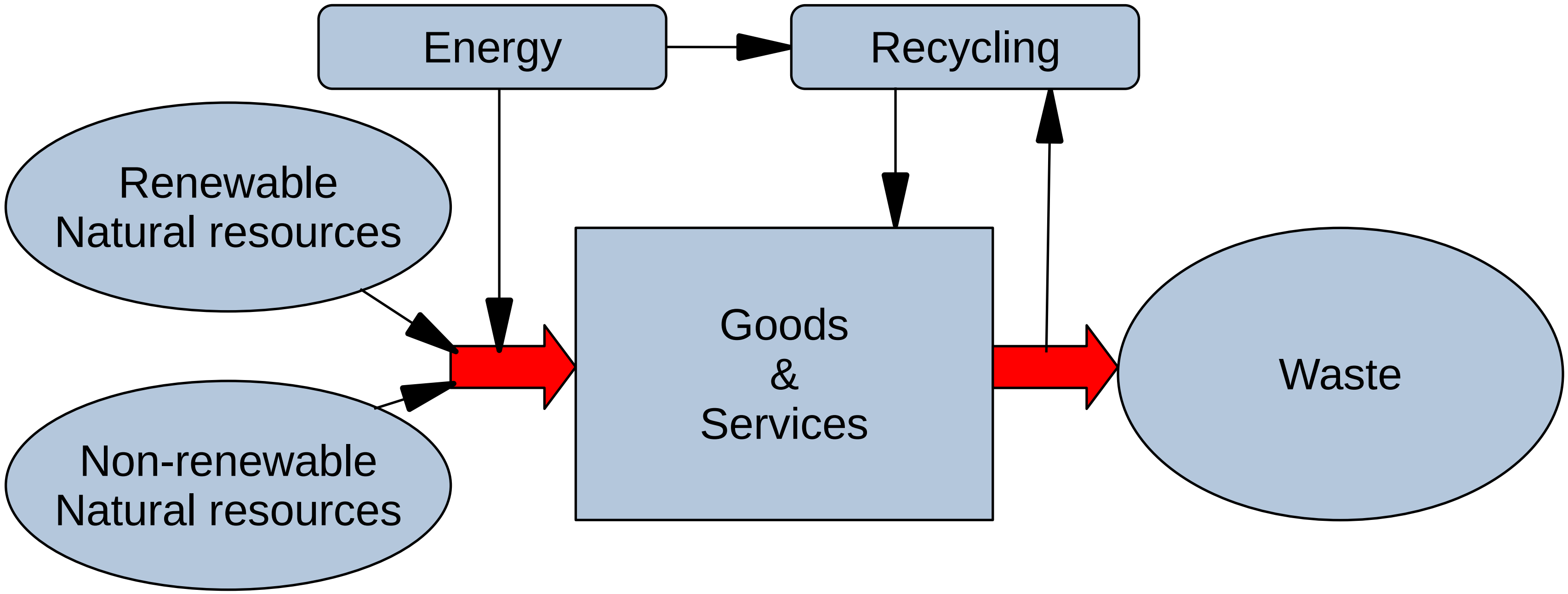
An equivalent diagram can be found in the figure 3.1 from **[1]**.



The key element for all fluxes: Energy

Physically, all transformation is performed by the use of energy. At the end of the use of a good or a service, we may recycle part or all of that, otherwise, ends up as waste in the environment. The process of recycling, which implies transformation, will require the use of energy. This diagram also introduces the distinction between renewable natural resources (solar energy and wind for example) and non-renewable natural resources (fossil fuels and most of the other elements extracted from the ground for example).

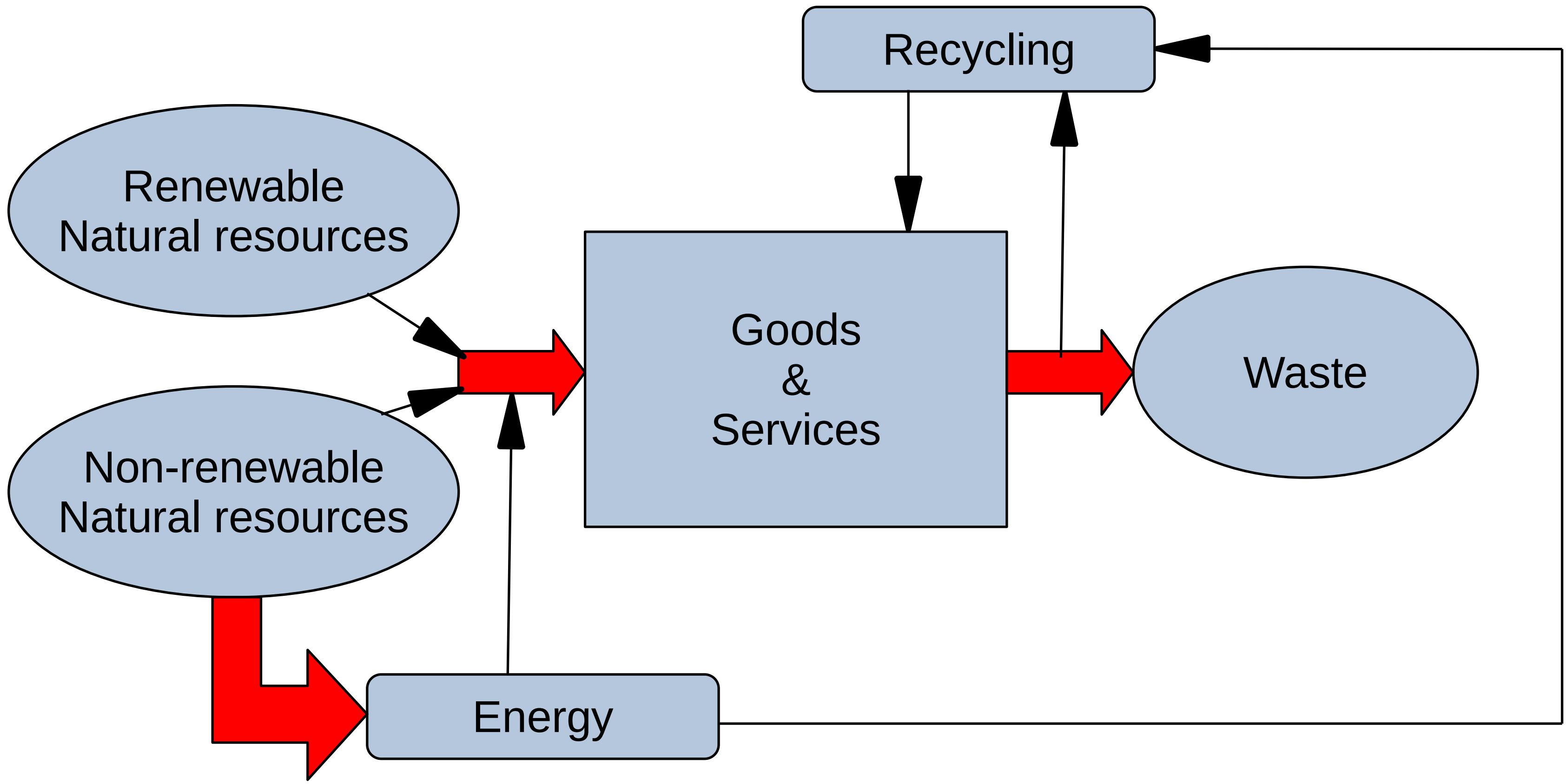
For a thorough description and analysis of this kind of diagram and dynamical system modeling, refer to **[1]**.



Non-sustainable global energy system

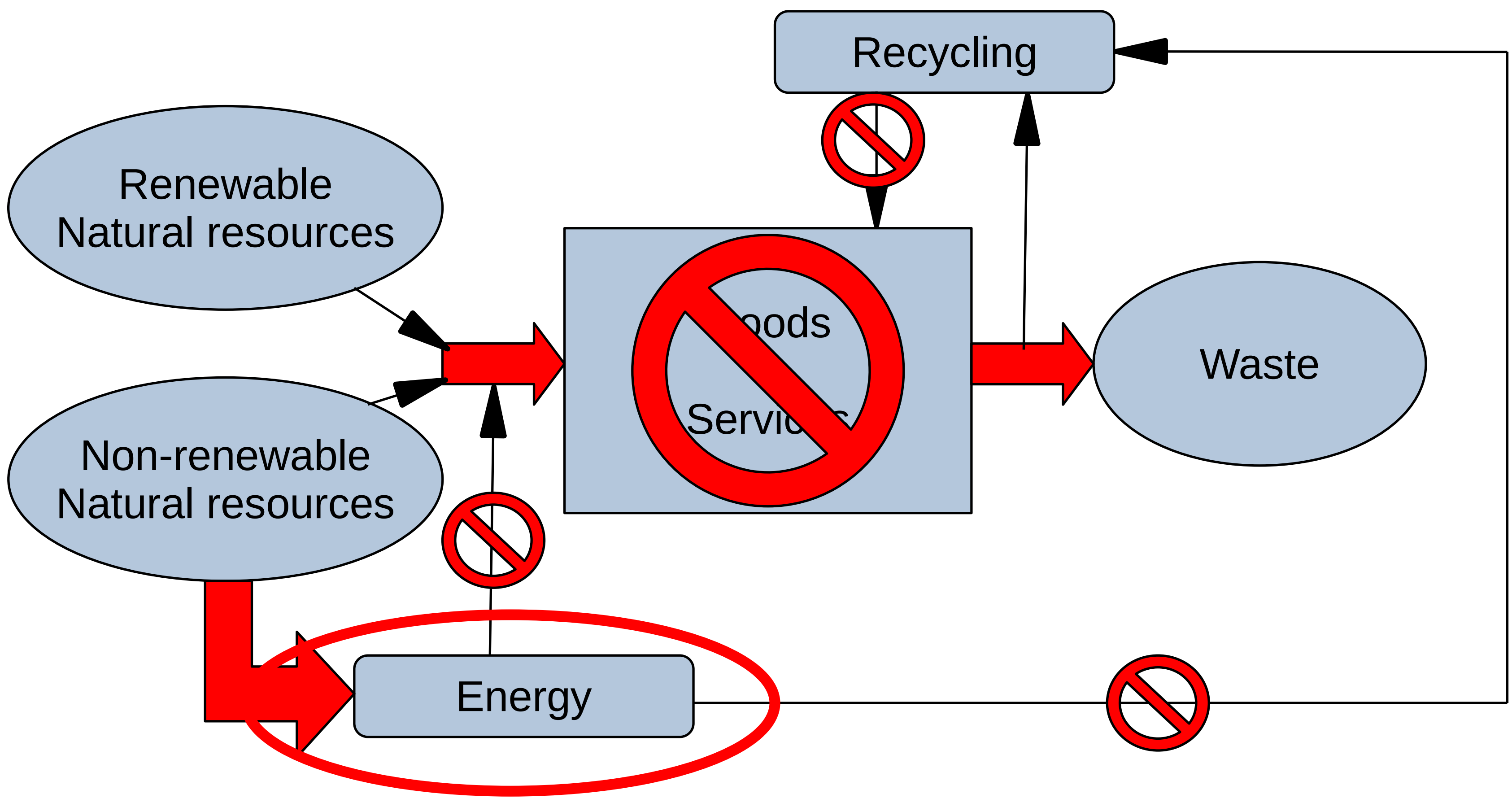
Today (2021), most of the energy we use to produce goods and services comes from non-renewable (actually fossil fuel) resources. Even when recycling products, we mainly use non-renewable energy resources. This means that our current production system in not sustainable in time.

More details on the positive and negative feedbacks of this kind of diagrams and dynamical system modeling analysis in **[1]**.



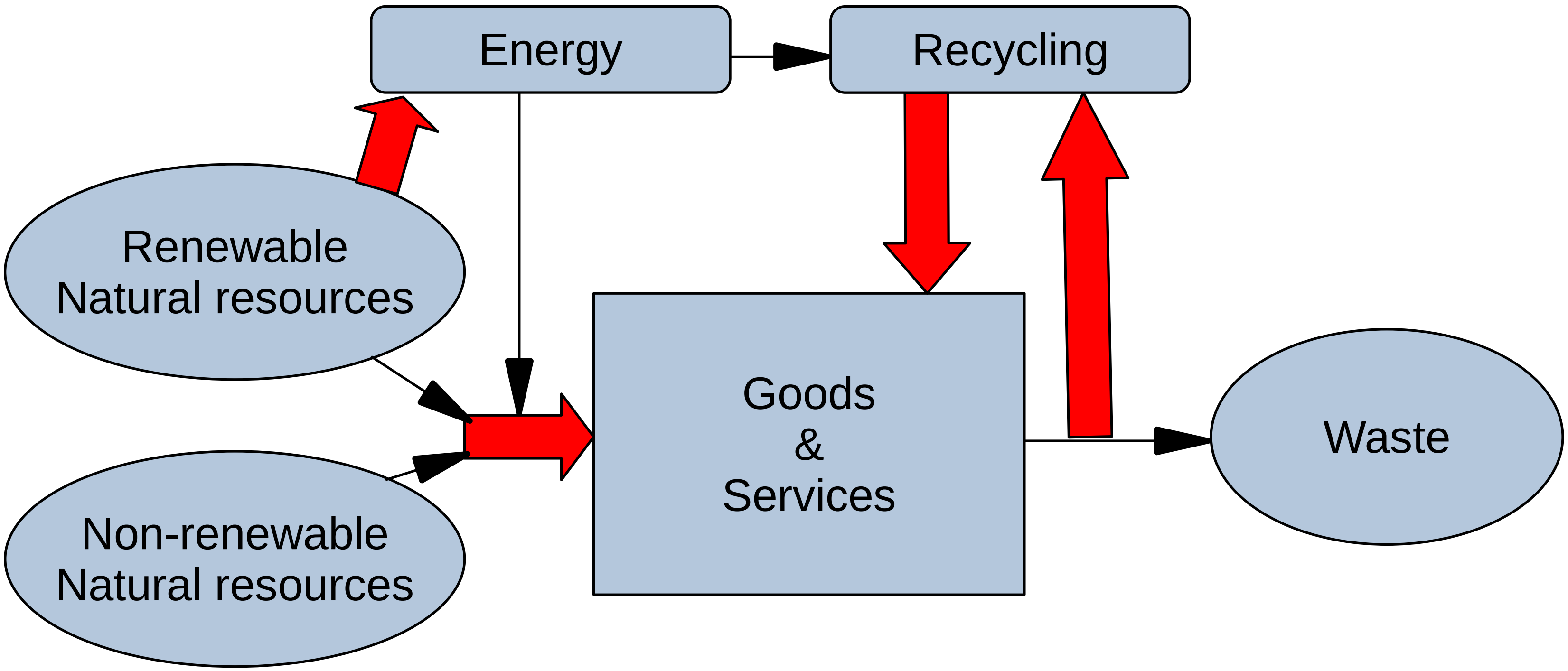
Non-sustainable global energy system

Of course, this diagram is extremely simple but aims at one specific target: showing the key role played by energy in this complex and worldwide system we live in. Without enough energy, basic goods or services could no longer be produced as expected.



Sustainable global energy system

The target we should aim at in terms of main fluxes for such system to become much more sustainable is the one below. Most of the energy used to produce all goods and services should come from renewable natural resources, and most of the goods and services should be recyclable and recycled.



How to ensure an **abundant** and **sustainable** energy supply worldwide?

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Non-sustainable sources of energy

Today's world energy supply system is obviously non-sustainable as it mainly relies on non-renewable energy sources. Nevertheless, we have to use the system we have today to build the sustainable one we need in a few decades if we still want to be able to produce the basic goods and services we are used to (food, transportation, education, health) and limit as much as possible the climate change consequences already at stake.

The energy supply system we have today has several advantages. There are three main features of this current system which make it so efficient and hard to replace by renewable energy sources:

1) All the non-renewable energy sources (fossil fuels, nuclear) we use are relatively **easy <u>to store</u>, <u>to transport</u> and <u>to control</u> when delivering the energy they carry**, meaning that we can chose where and when we want to use them.

2) They are also **<u>energetically dense</u>**, meaning that for a given amount of volume or mass, they can deliver a significant amount of usable energy. So, in terms of surface use at the ground, they represent a negligible fraction of the Earth's surface.

3) Globally, they are the **main primary energy source used to produce electricity** (mainly coal and gas), for which they hence contribute to ~20% of the total CO2 emissions per year *via* this human activity.

Focusing on electricity production

In the following slides, we are only going to focus on the energy sources used to produce electricity. Indeed, although the electricity we use in the world only represents ~15% **[2]** of the total final energy we use today, the electrical network will become more and more the dominant energy network worldwide if we want to replace as much fossil fuel sources of energy, and as fast, as we can.

There are three main sustainable sources of energy that can be exploited worldwide to produce electricity. For each of them, we stress the main features representing a disadvantage with respect to the non-renewable energy sources described above:

1) Hydro power can be deployed in many parts of the world, **but most of the potential of it has already been developed**. It is the only renewable energy source that we are able **<u>to control</u>** (with dams) in order to produce electricity whenever we need it, if the water resource is available, as are non-renewable energy sources.

2) Wind power can be developed almost anywhere in the world, even offshore. However, the major disadvantage compared to non-renewable energy sources is that the wind electricity production is **<u>highly variable</u> in time**, and **<u>hardly accurately predictable</u>**.

3) Solar power can also be developed almost everywhere in the world. However, compared to non-renewable energy source it is also **<u>highly variable</u> and <u>hardly accurately predictable</u> due to clouds**, and moreover **<u>intermittent</u>** since no power can be produced during the night.

Grid stability issues with current wind and solar power: production and storage oversize needed

These **high variability** and **non-predictability** features of electricity production characterizing wind and solar power make it very difficult for the electrical grid to cope with the consumption/production equilibrium needed to ensure the stability of the network. This is why today we still need large amounts of **controllable** energy sources in order to ensure the electrical grid stability.

If we want to get rid of the non-renewable energy source and still be safe in terms of electrical grid stability despite these two major constraints, two main features have to be added to such a 100% renewable energy source electrical power system:

1) Because of the uncertainty in electricity production and of some periods of inevitably low production (winter), an important infrastructure with significant power storage will have to be added to the electrical grid.

2) For the same reason and in order to find the best possible system optimization between ensuring a minimum electrical production at those winter periods and the largest but still reasonable storage capacity, the wind and solar production capacity will have to be oversized.

Addressing these two first issues will require to extract substantial extra materials from the ground which will likely encounter some mineral resources supply problems as discussed in **[3]**.

Other issues with current wind and solar power: land use competition, system complexity added

Besides these two system-design constraints for a 100% renewable energy source electrical grid based on the already available technologies, there are also a few system management constraints which are often not discussed about. Here are four of them:

1) If we want to produce enough electricity in order to satisfy our global final energy demand, the amount of surface needed to deploy all the solar and wind units needed for such power supply system would be quite large (between ~5% to ~10% of the land roughly), probably competing with other land uses as agriculture, biodiversity pools or human settlements/infrastructure.

2) If, in order to limit the land use competing problem, we plan to use already occupied area by humans as building or housing roofs, we will add a complexity to the electrical system management that is very difficult to evaluate. Indeed, if we have an electrical system based on tens or hundreds of thousands mid-to-small production units throughout an area like France, instead of the few hundreds or thousands large electricity production units which ensure the grid stability as it is today, how can we be sure that all the units expected to produce nominally will actually be producing the amount of electricity expected? Who will be responsible for the solar panels installed on a school or company roof not working properly and, hence, jeopardizing with the electrical grid stability? Will tens or hundreds of thousands captors disseminated throughout the country but connected to each other be able to “smartly” manage such a complex grid system? Will small energy consumers (companies or individuals) be constrain to, sometimes, not have electricity available when they need it?

Other issues with current wind and solar power: adaptation to climate change, contribution to it

3) Will the wind and solar power units deployed today be adapted to face changes likely to happen with climate change? This does not seem to be a major problem for wind turbines even if wind regimes might change in some areas with time. However, will PV solar panels still yield the production expected from them in summer when temperatures will reach increasingly warmer temperatures? Will their life cycle expectancy or performance rates still be the ones expected if exposed to those warmer summer temperatures?

4) If the PV solar panels are installed over brighter surfaces (more reflective in the solar spectrum) than their own, they will tend to locally decrease the near surface albedo (capacity to reflect solar radiation, having a cooling effect at the surface), hence having a warming effect at the ground level. If the surface on which the PV solar panel is installed is as dark as the panel one, then installing this solar panel will have a slightly cooling effect at the ground level (because of the fraction of energy transformed into electricity, hence not heating the surface anymore). As standard PV solar panel are quite dark, it is likely that, in most cases, installing the panel will have a slightly warming effect at the ground level locally. This might seem like a minor issue, but since the areas over which the PV solar panels will have to be deployed in order to achieve 100% renewable power supply are potentially very large, this might have an undesired surface warming effect which will further increase local and global surface temperatures. And as most PV solar panels will be deployed over the land, they will tend to warm even more the continents, which already warm faster than the ocean.

Is there a way to go beyond these systemic limits?

The objective of identifying these issues is not intended to deflect from a 100% renewable energy electrical supply system, which is an objective we have to reach if we want to build the sustainable energy system described in the first part of this presentation. We identified these issues in order to avoid new systemic flaws as the ones we have in our current global energy supply system (not sustainable and causing climate change). The more we foresee all the issues we might have to deal with in this journey towards a sustainable global energy supply system, the less systemic mistakes we are expected to make, increasing the chances to get faster on the right pathway to succeed in our endeavor.

Maybe a radical new kind of renewable energy power plant could help us in responding to those uncertainties that seem to make a 100% renewable energy electrical network much more complicated to achieve, and in the end also less efficient, than we could hope of.

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Solar irradiance is highly predictable above the clouds

There is a fundamental difference between the non-predictability associated to either wind or solar electricity productions.

Winds are roughly predictable a few days ahead thanks to atmosphere models and observations. However, there will always be uncertainties associated to it because of the wind nature itself: the atmosphere is a chaotic system, meaning that we will never have enough precision, in terms of description of the system at a given time, in order to determine for sure the intensity and direction of the wind there will be in a few days at a particular location.

This is not the case for the sun. The sun's irradiance at the surface is locally as chaotic as wind, but because of the clouds above it, which cannot be predicted accurately either basically because of the same reasons than for wind (+ inherent complex cloud formation processes). However, the sun's irradiance is perfectly predictable above clouds which cannot reach higher altitudes than the tropopause one (where a temperature gradient inversion occurs), roughly between 12 km and 16 km depending on the season and the latitude considered. This means that if we are able to deploy PV solar panels at such altitude, a great deal of the 100% renewable energy supply system inefficiencies we described before (production and storage significant oversize for grid stability, complex management of the grid because of its many mid-to-small production units widely spread) could be partly solved with a system based on PV solar panel located at the low stratosphere.

Defining an optimal structure to reach the sky and cope with all the constraints to take into account

The structure described hereafter, an innovative power plant based on PV solar panels named Light Tower of Babel (LTB), tries to take into account all the constraints that have to be dealt with in order to deploy such a structure in an optimized way to ensure its stability and maximize its energy production.

The structure is basically composed of three main parts:

1) A PV solar panel array of the order of 1 km² and its associated underlying structure to make all of it lighter than the surrounding air at the lower stratosphere.

2) A quasi-cylindrical tower, also lighter than the surrounding air it will be deployed across, which has to be approximately 15 km high and more or less 200 m of diameter (larger at the top of the tower, probably a bit less at the bottom of it). At the top of the tower, a mechanism allows to orient vertically the PV solar panel array, hence controlling its zenith angle.

3) A large scale building in which the PV solar panel array and all the cylindrical modules needed to build the tower can be stored and assembled before they are deployed. Once the tower is deployed, its lowest module (the bottom part of the tower) is mechanically coupled to a massive rotating cylinder which allows to orient horizontally the tower and the PV solar panel array at the top of it, hence controlling its azimuth angle.

A first description (in French) of this structure can be found in **[4]**.

Building a new global energy supply ecosystem: qualitative considerations

The structure described above does not make a lot of sens in a standalone approach. It has to be part of an ecosystem, which could become the main global energy supply system network, in order to deliver its full potential.

Indeed, to deploy such a light-weight tower and its PV solar panel at the top of it, significant amounts (thousands of tons) of hydrogen will be needed. So there has to be an important hydrogen storage capacity on site, and/or an access to large amounts of it *via* a hydrogen gas network (pipes).

Also, it would be interesting to associate to this tower an electrolysis plant in order to produce green hydrogen from the electricity generated by the PV panels at the top of the tower. The load factor of this electrolysis plant could be relatively high (near 50%) if permanently used whenever the tower is producing electricity.

Hence, we see that the green hydrogen produced by the first tower deployed could provide the hydrogen for the next ones to be deployed. That way, this energy supply ecosystem starts to build itself by deploying the two main networks it will be able to contribute to and on which it will also be built on: the electrical grid (already existing but which needs to be completed with more high voltage line interconnections within continents) and a hydrogen pipeline network.

Building a new global energy supply ecosystem: production estimates for one LTB

In order to have an idea of the orders of magnitude of the amount of power and energy we are talking about, here are rough estimates of the production for one LTB power plant:

Incident solar flux at the PV solar panels:	$S \approx 1300\, W/m^2$
Conversion rate (fraction of the solar flux effectively converted into electricity):	$n \approx 0.2$
Electrical power per surface unit:	$Ps = S \times n \approx 250\, W/m^2$
Total electrical power the LTB yields if the surface of the PV solar panels is 1 km²:	$Pe = Ps \times 10^6 = 250\, MW$
Total energy production estimate for a year:	$Etot = Pe \times 365 \times 11 \approx 1\, TWh$

A simple LTB numerical model has been developed and is available online **[5]** in order to allow anyone to understand and easily modify some few key variables of such a structure. This Python program estimates the masses of different parts of the structure and also computes energy and power production estimates depending on the values given by the user to these key variables that can be modified before performing a simulation.

Building a new global energy supply ecosystem: final quantitative considerations

Lets recall that the world's total annual electricity production is roughly 25000 TWh, about 15% of the total final energy consumption worldwide **[2]**. Let us assume we would need 50 km² of land to safely deploy an LTB. If we would like to produce the double of the electricity produced today (50000 TWh) with an energy supply system only based on LTB structures, in order to significantly reduce the greenhouse gas emissions coming from our total final energy consumption, we would then have:

Hypothetical total land surface needed to deploy 50000 LTB to significantly reduce energy consumption-related greenhouse gas emissions :

$$Surf_{tot} = 50 \times 50 \times 10^3 = 2.5\ Mkm^2$$

A land surface of 2.5 million km², corresponding to ~3% of the total land cover of the globe, seems like a reasonable/acceptable fraction of the total land surface to allocate to what could produce most of the energy needed by mankind.

Having these preliminary numbers in mind, let us try to imagine a possible deployment scenario in order to achieve this hypothetical target.

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Global energy supply system transition scenario: how to start

In this part of the presentation, a possible transition scenario for the XXI century, going from our current and unsustainable greenhouse gas emission-intensive global energy supply system to a mostly LTB-based and more sustainable one, is described. The main milestones of this pathway are exposed trying to take into account what we believe are the most important elements to keep in mind in this highly hypothetical scenario.

1) The starting point hypothesis that has to be done is the following: soon enough, most countries of the world agree they will have to strongly cooperate with each other in order to properly address this double climate change-energy supply major issue, the greatest challenge humankind has had to face so far. They understand the promising features that a LTB-based energy ecosystem would have on both components of the problem. In order to initiate this massive transition, they agree on collaborating in an unprecedented way by accepting to share all technological or industrial process development related to the needs for deploying such new energy ecosystem.

2) Technologies to deploy LTB power plants have been successfully and rapidly developed thanks to the strong international scientific/technical collaboration. All countries willing to start massively deploying such towers (thousands or hundreds, not less) commit to dismantle, as LTBs are deployed, all or as many fossil fuel power plants they have on their territory, starting with coal power plant in priority, followed by natural gas power plants. International financial investments are then allocated to those countries/companies to start building this new energy networks.

Global energy supply system transition scenario: where to start

3) An important point has to be addressed concerning the areas where to deploy LTBs. Such towers cannot be deployed anywhere in the world. By design, and after they have been deployed in favorable weather conditions, the tower and the surface building surely have to be able to resist to strong winds, rain, snow, hail and even lightning. But these towers do not have to be deployed where hurricanes or particularly strong storms are likely to happen in the XXI century's changing climate. Also, the best places where to deploy such towers would be in areas relatively far from where large human settlements are found, in case of an accident. All these constraints point to the Northern Hemisphere (NH) mid-to-high latitude lands, like the West and North of China, Russia, Scandinavian countries, the North of the United states and Canada. Starting the LTBs deployment in such areas also have another strategic advantage: the top of the LTB will produce a shadow at the Earth's surface, which will move throughout the day and the seasons over an area of ~100 km^2 depending on the latitude where the LTB is located. This will locally cool the surface in a non-negligible way, particularly if LTBs are relatively close to each other in the considered area. This phenomenon would be particularly interesting in the NH high latitudes which are the Earth's areas that are warming the fastest with climate change. By slowing down such relatively local and faster warming, we should allow the snow-ice cover appearing on these surfaces during the winter to last longer and subsequently reflect more solar radiation reaching the surface after the winter season, hence further keeping the surface cool. In other words, **this would slow down the surface temperature-albedo positive feedback already at stake in those northern regions**, partly responsible for the faster warming already happening there.

Global energy supply system transition scenario: social habits and the electrical grid stability

4) As the energy supply system deeply changes in this scenario, the way we use energy, and particularly electricity, will have to change as well. This major systemic change is actually about the way we connect to our environment and particularly to its primarily energy source: the solar flux. So far we have based our astonishingly fast development on solar power that have been concentrated and stored on geological times. If we really want to get as close to a sustainable system as we can, then **we have to manage to base as many of the mass and energy fluxes that are at stake in human activities on this quasi-periodical and fully predictable, <u>at the lower stratosphere</u>, solar energy flux** which is driving all of the environment we evolve in. Here is an example to illustrate this.

In this transition scenario, the more we use energy during daytime, the more we will be using the electricity produced by the LTBs, hence practically directly using the energy flow delivered by the sun. In a sens, we directly connect or “wire” our activity to the sun’s energy flux, the conversion or storage costs are as minor as they can be for the system in this case. Any energy we use when the sun is gone will require extra costs in terms of storage capacity or long-distance transportation. This means that, as we will collectively try to decrease as much energy and material costs as we can, we will tend to concentrate our activities during daytime in order to optimize such costs. Of course, we will still use electricity when the sun will be below the horizon, but as society will move towards sustainability it will try to concentrate all energy-intensive activities (industry, transportation) **when the primary source of energy will be flowing in a predictable way into the system**, during daytime.

Global energy supply system transition scenario: LTB main features

5) As the new energy and electricity use paradigms make their way, the more LTBs will have to be deployed to satisfy in an optimal manner to this new electricity consumption daily cycle, ensuring a not too massive nor excessively resource-consuming energy storage system. Here we want to highlight some fundamental features LTBs should have.

Ideally, all LTBs have to be built exactly the same way, and the design of this standard LTB has to fulfill the following basic requirements in order to be as sustainable as we want the energy supply ecosystem to be:

- No important amounts of critical minerals are needed to build the LTB.
- Most parts of the LTB, particularly the ones that will have to be changed regularly in time (every X years) in order to keep the LTB running safely have to be completely recyclable.
- All of its structure has to be as modular as possible, in order to automate all of the deployment/storage processes.
- Many critical parts of the LTB structure have sensors in order to monitor in real-time the state of the entire structure.
- The LTB deployment/storage processes have to be prepared days in advance with regional modeling simulations ensuring the most favorable weather conditions to such crossing of the troposphere by the PV solar panel array, which should probably take tens of hours, but also have emergency procedures in case the tower has to be brought back to surface as safely as possible, no matter the weather conditions.

Global energy supply system transition scenario: industrial strategies to deploy LTBs

6) All LTB have to be built the same way for industrial development issues, so that every large scale machine developed to build LTB parts can be used to assemble many LTBs. This brings to light the way LTBs could be deployed regionally and form multi-LTB power generating industrial areas which could all be built in the same following way:

- The large-scale machines needed to build all the LTB parts are constructed in site.
- A first LTB is constructed and deployed in the area, allowing to start electricity and green hydrogen production for the next LTBs to be constructed and deployed.
- As a substantial part of the mass of the LTB (~10%) is hydrogen, and as the electricity produced by the first LTB deployed is partly used to build the next ones, the carbon footprint of the following LTBs is going to decrease significantly and steadily as we deploy more and more of them.
- Once tens or hundreds of LTBs have been deployed that way, this energy ecosystem is **ready to produce and deliver large amounts of predictable electricity and hydrogen during daytime** to national and/or international electricity and hydrogen networks.

Global energy supply system transition scenario: full sustainability in time is the final target

7) In the best case scenario, in a few decades if climate change and/or human beings do not manage to jeopardize this hypothetical but in many ways desirable plan, when approaching the tens of thousands LTBs deployed throughout the world, the world energy supply system will be highly efficient and very close to be fully sustainable, because it will be massively based on the solar energy flux. If we manage to develop new recycling techniques, re-build most of our industrial processes so that, by design, all our goods and services may end up in this major recycling industry, we may even approach a global physical state in which all mankind activities will no longer have any last-longing environmental footprint, besides the ones related to past activities that will slowly, but surely, dissipate with time.

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Conclusions

In this last part, we summarize what the major features the LTB-based energy supply system presented in this document are:

1) Vertically extending the already widely existing electrical grid network in order to get to the altitude (low stratosphere) **where the solar energy resource becomes predictable**. At that altitude, optimal conditions allow to maximize the electricity production from light-weighted PV solar panels by being in a cold and stable environment and by being able to freely orient the LTB's PV panel array so it constantly points towards the sun's position.

2) The only part of the LTB that should not be considered as being part of the electrical network are the PV solar panels that will have to be replaced every 20~30 years (as for standard ground-based PV panels), in order to keep ensuring with time the best possible conversion rate from the sun's irradiance into electricity. With such long-lasting vertical structures ready to be deployed, we will directly, and in the most optimal way, benefit from PV panel technological advances (as better conversion rates) without any supplementary infrastructure cost, just by replacing the old PV panels at the top of the LTB by the higher-performance new ones.

3) Another important feature of LTBs is the *a priori* simple way they will be able to adapt to climate change conditions. Indeed, if at the ground level no significantly storm regimes start to emerge in that particular location, the only thing each LTB will have to do to adapt to climate change is deploying its tower a little bit higher (hundreds of meter) because of the atmosphere dilation caused by warmer temperatures, consequently slightly rising the tropopause altitude everywhere. No changes in surface water resources or temperature will affect the electricity production performances of the LTBs.

Conclusions

4) Also, the LTBs, by projecting a moving shadow at the ground level wherever they will be deployed on Earth, will tend to locally cool the surface, which might slightly slow down local surface warming. This feature would be particularly interesting in the high-latitude NH where this cooling effect might slow down the surface temperature-albedo positive feedback already at stake there and partly responsible for the faster warming of these Northern land regions.

5) Nevertheless, this new infrastructure is so innovative, so ambitious, that everything has to be invented in order to effectively deploy such LTBs across the atmosphere. We will need unprecedented international cooperation, new rules for the airspace governance, and also opened and widely shared industrial/scientific developments. **These Light Tower of Babel structures are fragile by design, that is where they get their name from: If we do not manage to cooperate and understand each other in this major endeavor in order to reach the sky, gathered together around this needed sustainable global energy supply system project, we risk collapsing collectively**. In other words, we might have to accept this shared vulnerability if we want to keep most of the progress human beings have created for themselves so far.

6) Current market/economics/financial rules or tools have not been able to put us in the right pathway towards sustainability. In order to succeed in developing such unseen and ambitious international project as the one presented here, we will probably have to change some of these current rules that have been highly inefficient to properly address the climate change challenge we face and our system’s sustainability problem, which are long-term issues, for which markets seem utterly blind to.

Conclusions

7) In their recent Net Zero Emission by 2050 scenario **[6]**, the IEA could not put it any better:

Net Zero by 2050 – Analysi

iea.org/reports/net-zero-by-2050

Cite Share Full report ↓

Priority action: Take international co-operation to new heights

This is not simply a matter of all governments seeking to bring their national emissions to net zero – it means tackling global challenges through co-ordinated actions.

Governments must work together in an effective and mutually beneficial manner to implement coherent measures that cross borders. This includes carefully managing domestic job creation and local commercial advantages with the collective global need for clean energy technology deployment. Accelerating innovation, developing international standards and co-ordinating to scale up clean technologies needs to be done in a way that links national markets. Co-operation must recognise differences in the stages of development of different countries and the varying situations of different parts of society. For many rich countries, achieving net-zero emissions will be more difficult and costly without international co-operation. For many developing countries, the pathway to net zero without international assistance is not clear. Technical and financial support is needed to ensure deployment of key technologies and infrastructure. Without greater international co-operation, global CO_2 emissions will not fall to net zero by 2050.

References

[1] Meadows, D., Randers, J., and Meadows, D., 2012. *The limits to growth: the 30-year update*. Routledge.

[2] https://www.iea.org/data-and-statistics

[3] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[4] https://data.inpi.fr/brevets/FR3059763?q=#FR3059763

[5] https://github.com/rodguzmanr/LTB

[6] https://www.iea.org/reports/net-zero-by-2050