Luxembourg 2050 – Prospects for a Regenerative City-Landscape

Report Phase 1

University of Luxembourg (UL)
Luxembourg Institute of Science and Technology (LIST)
Centre for Ecological Learning Luxembourg (CELL)
Institute for Organic Agriculture Luxembourg (IBLA)
Office for Landscape Morphology (OLM)

Luxembourg 2050 – Prospects for a Regenerative City-Landscape

Report Phase 1
4 I 1 I 2021

University of Luxembourg (UL)
Luxembourg Institute of Science and Technology (LIST)
Centre for Ecological Learning Luxembourg (CELL)
Institute for Organic Agriculture Luxembourg (IBLA)
Office for Landscape Morphology (OLM)

Intermediate Report January 2021

“Luxembourg 2050. Prospects for a Regenerative City-Landscape”

This report summarises the collaborative work of University of Luxembourg (UL), Luxembourg Institute of Science and Technology (LIST), Centre for Ecological Learning Luxembourg (CELL), Institute for Organic Agriculture Luxembourg (IBLA), Office for Landscape Morphology (OLM) and encompasses the teams' contribution to the International Urban-Architectural and Landscape Consultation “Luxembourg in Transition. Spatial Visions for the Zero-Carbon and Resilient Future of the Luxembourg Functional Region”, initiated by the Ministère de l'Energie et de l'Aménagement du territoire / Département de l'Aménagement du territoire (DATer).

Team

Coordination Committee
The coordination committee is composed of co-moderators of the working groups (WG) on urban regeneration, energy transition, agro-ecology, post-growth economy, and transition participation.

Prof. Dr. Florian Hertweck, PI, co-moderator WG urban regeneration (UL)
Dr. Enrico Benetto, co-moderator WG post-growth economy (LIST)
Dr. Arno Biwer, co-moderator WG transition participation (LIST)
Dr. Thomas Gibon, co-moderator WG energy transition (LIST)
Dr. Claudia Hitaj, co-moderator WG agro-ecology (LIST)
Dr. Sylvain Kubicky, co-moderator WG urban regeneration (LIST)
Dr. Markus Molz, co-moderator WG transition participation (CELL)
Karine Paris, co-moderator WG agro-ecology (CELL)
Norry Schneider, co-moderator WG energy transition (CELL)
Prof. Dr. Christian Schulz, co-moderator WG post-growth economy (UL)

With contributions from:

University of Luxembourg (UL)
Tom Becker
Dr. Estelle Evrard
Prof. Dr. Jean-Régis Hadji-Minaglou
Prof. Dr. Joachim Hansen
Prof. Dr. Markus Hesse
Dr. Nikolaos Katsikis
Dr. Ariane König
Prof. Dr. Christoph Odenbreit
Dr. David Peleman
Dr. Rachel Reckinger
Prof. Peter Swinnen
Prof. Dr. Francesco Viti
Prof. Dr. Danièle Waldmann
Ivonne Weichold

Luxembourg Institute of Science and Technology (LIST)
Dr. Jürgen Junk
Dr. Antonino Marvuglia
Dr. Benedetto Rugani

Centre for Ecological Learning Luxembourg (CELL)
Delphine Hardy

Institute for Organic Agriculture Luxembourg (IBLA)
Dr. Sabine Keßler
Laura Leimbrock-Rosch
Evelyne Stoll
Dr. Stéphanie Zimmer

Office for Landscape Morphology (OLM)
Philippe Coignet

Student assistants (UL)
Aisha Abdullah, Eldin Babic

Layout
Aisha Abdullah, Prof. Dr. Florian Hertweck

Design Research Studio
Parallel to research a design studio on the theme of the call for tender has been led at University of Luxembourg by Dr. Nikolaos Katsikis and Prof. Dr. Florian Hertweck

Design Studio Students
Christos Floros, Daniel Domine, Simona Popova
Raphaela Sarah Aurelia Sauer, Vivian Torres
Piotr Pawliszyn, Diana Valentina Zarnescu
Andreea-Alexandra Paraschiv, Kalpana Dushyanthi Piyadigamage, Nazanin Mirsharifi
Marina Caroline de Araujo Marins, Soroush Najarsaleh

Jan 2021

I. INTRODUCTION

II. METRICS

III. PROSPECTS

I. INTRODUCTION

01 Structure of the Report and Guiding Principles

The call for tender requires the teams in this first stage of the consultation to develop a metric system, able to simulate and monitor the ecological transition, which is then applied in a second stage to the functional space of Luxembourg. From this ambition, we derive two methodological postulates: First, the metric system cannot be generic, but must refer to this singular territory with its specific socio-economic, political, cultural and anthropological conditions. Secondly, at least the contours of the vision for this space in 2050, as called for by the ecological transition defined by these metrics must be outlined.

Spatial visions, or the more precise French term *prospectives*, differ from scenarios in that they represent a future as it should be – here in relation to the goals of decarbonisation and resilience – rather than as it could be under the assumption of certain developments. That is, unlike scenarios, visions refer less to the probability of a certain trajectory and instead to the plausibility of a desired imaginary. However, our vision is grounded in the decarbonisation and resilience targets for 2050 with a back-casting strategy that defines the paths and sequences of decisions, measures, and projects. *Prospectives* offer a narrative for a distant future – even if the timespan of 30 years is dwarfed by the imminent challenges of climate protection. A narrative is needed that is holistic and at the same time more open than a master plan, because various developments are not yet foreseeable. And it must be strong enough to unleash collective creativity, stimulate public debates and orient day-to-day political business, so that the right steps are taken today and every day over these 30 years to make resilient decarbonisation by 2050 possible.

These methodological questions and challenges give rise to the following structure: In a first step, we present our analysis of this region and in doing so, we investigate why the functional transnational space of Luxembourg is particularly challenging for advancing the socio-ecological transition towards the ambitious climate goals. In order to work out a convincing vision, it is first necessary to acquire a profound knowledge of the territory and then to abstract this knowledge so that fresh ideas can be developed, which in turn are then tested in this space. Visions thus always oscillate between a real space and an ideal space. Without a relentless problem statement, however, every idea, as fresh it might be, lacks grounded realism. In this second chapter, we show that Luxembourg has already reinvented itself several times at important junctures of its history, which indicates a unique potential for overcoming the contemporary challenges mentioned above.

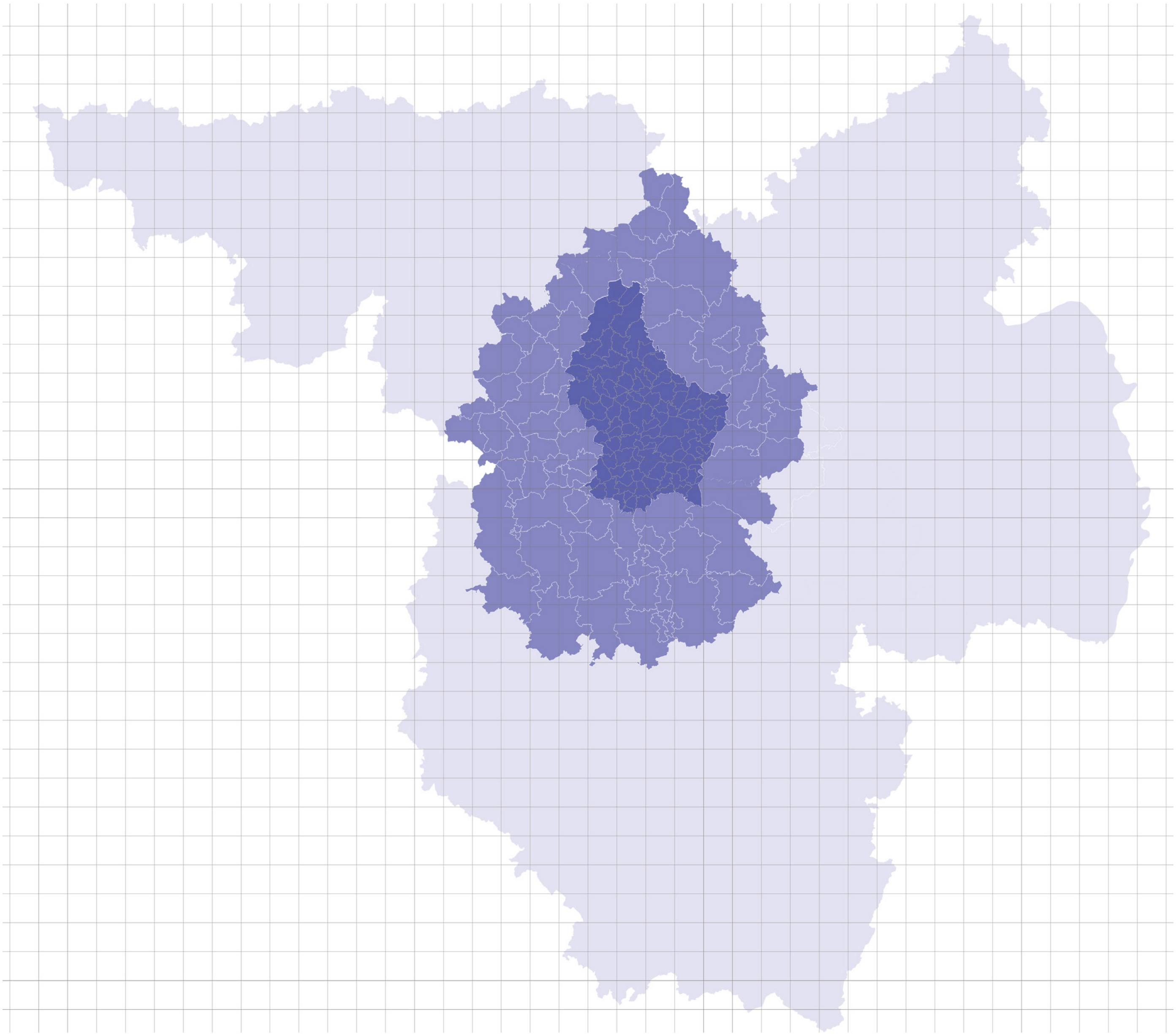


Figure 1. Territories of intervention

Greater Region
Functional Space of Luxembourg
Luxembourg the country

The introductory problem statement is followed by our framework of metrics for an ecological transition, which demonstrates how this fossil energy-intensive territory can be decarbonised by 2050. In doing so, however, it is important to us that the proposed decarbonisation pathway does not cause collateral damage in other ecological areas such as biodiversity, nor undermine the well-being of the citizens. For this reason, we chose the integrative Doughnut Economics Model (Raworth 2017) as an overall framework, since it measures sustainability progress as staying within ecological ceilings and meeting social thresholds. Amsterdam, which is similar in size with its 864,000 inhabitants to the Luxembourg functional region, took the global lead by adopting and contextualising this model to guide its transformation into a 100% circular city-region by 2050 (Raworth 2020). Thus, our metrics framework combines the two themes of the call: decarbonisation and resilience.

Our objective is to reduce annual per-capita greenhouse gas (GHG) emissions from 13 to 1.6 t CO_2 eq. by 2050 while meeting a set of resilience constraints formulated as ecological ceilings (maxima) or social foundations (minima). Our ecological ceilings relate to particulate matter, sulphur and nitrogen oxides emissions, nitrogen and phosphorus emissions, materials and blue water use, while our social and environmental foundations include indicators for carbon uptake, biodiversity, soil sealing, social justice, and life satisfaction. We take a life-cycle approach, measuring the global impacts of Luxembourgish consumption. Armed with this metric framework, we propose many interventions and measure their impact on GHG emissions and our set of ecological and social constraints, in order to select a set of interventions that put Luxembourg on a resilient decarbonisation path. We then elaborate the spatial and temporal implications of these interventions in a second step.

Our selected interventions for decarbonisation and resilience have several features in common. Three overarching value-based guidelines characterise our set of interventions: post-growth/sufficiency, spatial justice, and regenerative sustainability/urban regeneration. The spatial and temporal interplay of our interventions based on these guidelines define our vision for Luxembourg in 2050 and our specific decarbonisation path to attain this goal.

Our vision for a zero-carbon and resilient future of the Luxembourg region is shaped more concretely by eight principles:

1. A regenerative city-landscape defined as an intense and close relationship between the urban (in all its diversity) and the natural (in all its diversity).

2. A significant reduction of mobility needs defined as the 15-minute-city principle, by decentralising companies, institutions and amenities, by transforming the organisation of work itself, by dividing the big into smaller structures in our five fields (spatial planning, agriculture, energy, economy, governance), and finally by radically diversifying functions across the different granularities of the territory.

3. Porosity by not developing any more buildable land and thus transforming these vacant lots into productive land, such as urban farming or urban forests; but also social and cultural porosity.

4. Less than no net land take and thus a strong re-naturalisation of sealed land by a completely new land use strategy regenerating the land of the fossil age.

5. The triple zero in the building sector: zero CO_2, zero energy consumption, zero waste for the building lifecycle: construction, maintenance, retrofitting and deconstruction.

6. The regional sharing economy, with cooperative and commons-based platforms for sharing the use of spaces, goods and transportation.

7. Food sovereignty, including the reduction of GHG-intensive food and of food waste.

8. The introduction of a genuine transition governance (multi-level and multi-domain, cross-sector and cross-border), based on the principle of open participation of all concerned and of all affected interests and requiring governance innovations and experimentations accompanied by capacity building for accelerated social learning.

We conclude with a draft of our vision, as well as an outlook of what we intend to do in the second phase – a systematic spatialisation and sequencing of our interventions combined with an exchange with local pioneers –, and what we intend to do in the third phase – the projection of this perspective in concrete, emblematic sites that have the potential to become transition hotspots.

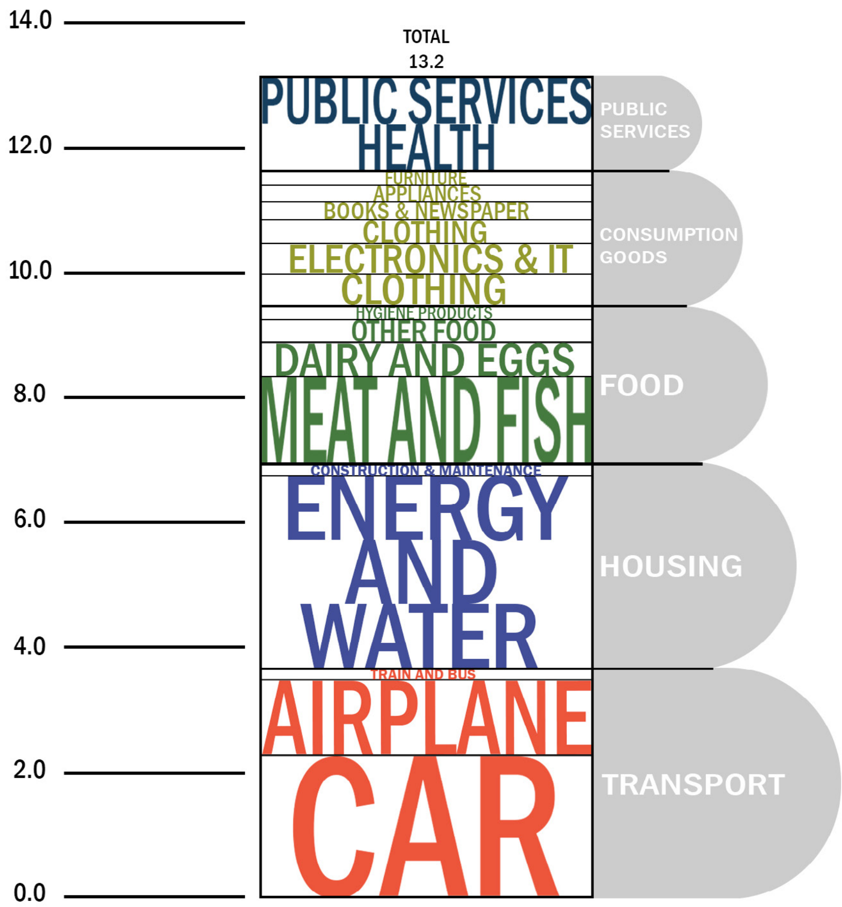


Figure 2. Carbon footprint of the average Luxembourger by consumption category (t CO2 eq. per capita)

02 Fossil Luxembourg or the Urgency of an Ecological Transition

Luxembourg has the highest Ecological Footprint with 7.8 planets and by far the highest Carbon Footprint in Europe with 15 t CO_2 eq. emissions per inhabitant (Keßler et al. 2020).[1] Last year, its Country Overshoot Day, i.e. the day on which Luxembourg used up its resources in relation to the size of the country, occurred on February 15, the earliest in Europe (Country Overshoot Day 2020). At the same time, the Grand Duchy, as a relational country, is disproportionately dependent on international capital, on regional and international goods and labour, and finally on imported food. This deficient resilience, which has become particularly apparent in the current pandemic, also applies to the effects of global warming, with heat waves, forest dieback and the continuous decline in biodiversity in the region.

How does it come that an original agrarian and today mostly post-industrial country has such above-average adverse effects on the climate and that it has become so dependent and so unprepared to the effects of climate change?

[1] This value of 15 t CO_2 eq. corresponds to emissions from production; on the other hand, we estimate (resident-only) consumption emissions to be 13 t CO_2 eq.

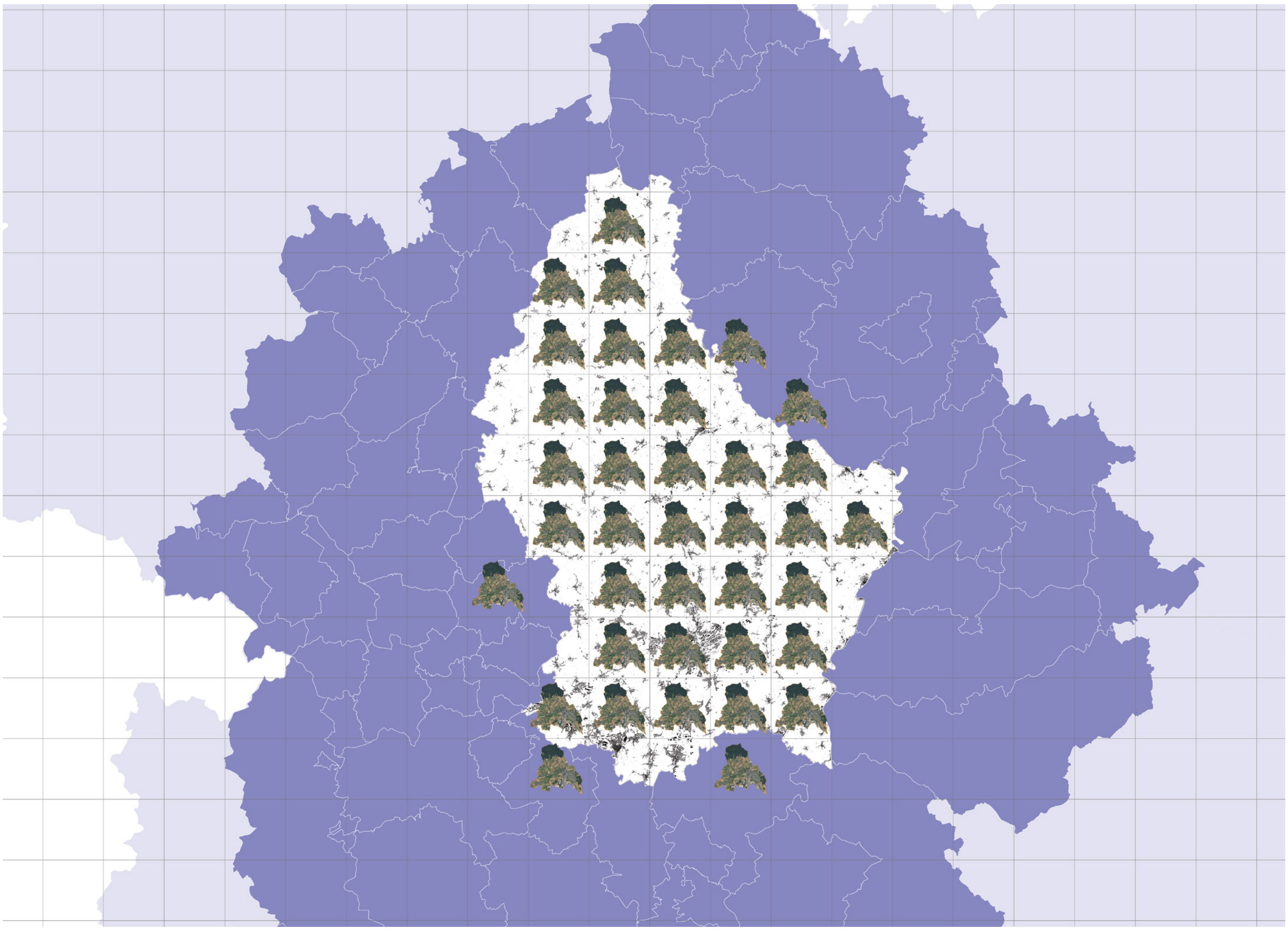


Figure 3 - 33 Bettembourgs
A projection of 33 new Bettembourgs on the functional space of Luxembourg to fulfill the demand in terms of housing for an expected 400k new inhabitants until 2050 that simulates dimension of the built-up areas we are facing.

Growth paradigm and functional fragmentation

With a gross domestic product of close to €100,000 per capita,[2] Luxembourg is at the top of Europe compared to the OECD average of €38,000 and continues to grow at above-average rates (OECD 2020). Over the last half century, it has developed in the shape of "small-but-global" urbanisation, with "borrowed size" creating a fundamental mismatch between economic power and wealth on the one hand, and territorial properties (size, resources, human power, infrastructure) on the other hand. Having established itself initially as one of the administrative centres of the European Union and as a banking location following the decline of the steel industry, it has now gained a leading position for investment funds and tech companies over the last two decades thanks to its political-economic and fiscal policy strategy. In the meantime, about 4,000 investment funds and tech companies such as Amazon or Microsoft are located in Luxembourg (Investment Funds in Luxembourg 2020). The export of services and goods amounts to 225% of the GDP compared to an OECD average of 29% (OECD 2020). Next to financial services, fossil fuel intensive goods, such as iron and steel, components for cars and lorries, industrial pieces, and metal waste are exported (OECD 2020).

[2] The usual per capita representation of the GDP is frequently criticised for being misleading in the case of Luxembourg given the high number of cross-border commuters contributing to and profiting from the domestic economic performance. However, even if one included the commuters as if they were residents, the per capita GDP would still remain the highest in Europe.

Strong economic growth and high salaries have led to an exponential increase in the labour market from 211,000 jobs in 1995 to 477,000 in October 2020 (STATEC 2020a). As a result, economic growth has also triggered demographic growth that is unparalleled in Europe. The Grand Duchy's recent demographic growth has been steady and continuous; since 1981, its national population has increased by almost 70% to 620,000 inhabitants as of January 2020 (Becker & Hesse 2020). Over the last five years it has recorded an annual population growth rate of 2.2 %. A new Bettembourg would have to be built every year if the new inhabitants were to be accommodated in a new city alone.

Investment in infrastructure and housing lags behind this rapid growth. The supply of housing is far from keeping pace with the increasing demand: on average, only 2,500 new dwellings are built each year, figures rarely exceeding the 4,000 mark (STATEC 2020b). Instead, tertiary estates have been built in central locations to meet the demand for office space. Housing construction is dominated by private developers and private owner-occupiers, since until recently, state housing policy was limited to promoting owner-occupied housing. The home ownership rate of over 70% is above average by international standards. There is no diversification of actors and housing types in housing production, neither as cooperatives, nor as building groups, and the share of social housing in total housing construction is less than 3 %. Thus, what Lucius Burckhardt stated in general terms 40 years ago also applies to Luxembourg: “The liberal belief that demand for housing creates supply has been in need of proof for a hundred years" (Burckhardt 1981).

Land ownership is extremely unevenly distributed. For example, 1,000 inhabitants own 32% of the total national land ready for building, and in Luxembourg-City as much as 63% of the land is owned by 11 families and 11 companies (Observatoire de l’Habitat 2019). In contrast, the public authorities own only 11% of the total buildable land (Observatoire de l’Habitat 2019). If all the plots of land designated as buildable in the development plans with a total area of 2,846 ha were developed, it would be possible to produce around 50,000 to 80,000 dwellings for between 100,000 and 150,000 inhabitants, to cover demand to a large extent and thus to push the inner development of cities in Luxembourg (Logement.lu 2019). According to Antoine Paccoud, the housing shortage is due less to the availability of building land than to its mobilisation (Paccoud 2019).

The result of this gap and the enormously high housing prices associated with it (STATEC & LISER 2018)[3] – 42% of the average household income of the 20% most vulnerable households is used to finance housing (STATEC & LISER 2018) – is that an increasing number of new residents move into peripheral municipalities and across the border. The number of daily cross-border commuters into the country exceeds 200,000, half of which come from the French neighbouring regions. More than 45 % of employees in Luxembourg commute from outside the country every day – mainly by car (STATEC 2020c). Therefore, transport accounts for more than half of all GHG emissions (OECD 2020). The expansion of Findel as one of Europe’s Top-5 hubs for air cargo traffic also contributes to the high share of transport in Luxembourg GHG emissions. A final factor is the phenomenon of “fuel tourism”. Since petrol is taxed very lightly in Luxembourg compared to neighbouring countries, petrol stations along the border are sought

[3] And housing prices continue to rise by an average of 6% each year.

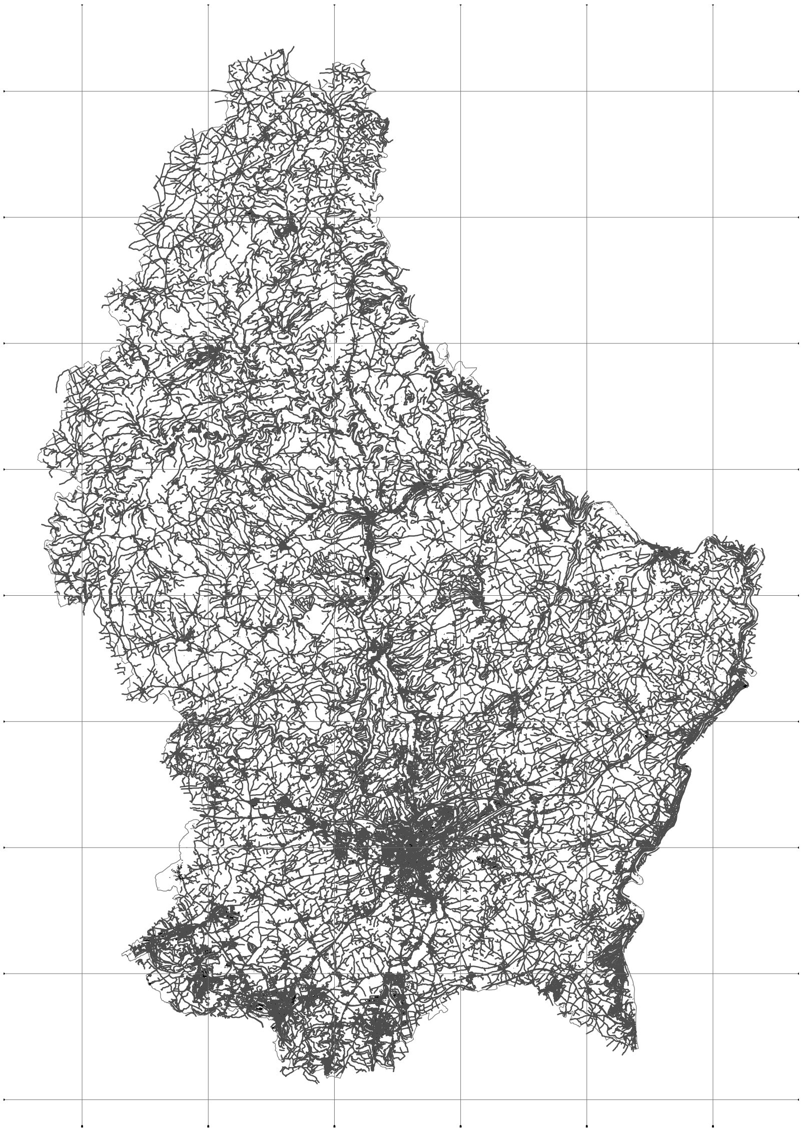


Figure 4. Map of Luxembourg's road infrastructure and urban fabric

by residents throughout the region, while lorries schedule the country as a stopover to refuel. In addition, tobacco and coffee are taxed relatively lightly, which further stimulates fuel tourism near the border. As a result, many motorways and rural roads are congested, and mobility has become almost dysfunctional with a negative effect on life satisfaction as well (Caruso et al. 2020; STATEC 2020d).

As a result of the demand for land for housing and infrastructure, built-up land has increased to 311 m^2 or 12% of Luxembourg's land area. The results are particularly strong in a small country like Luxembourg: "This development inhibits the natural functions of soils, contributes to the fragmentation and degradation of natural habitats, and increases the pressure on biodiversity, which has been in decline for more than forty years" (OECD 2020). Two thirds of natural habitats are in a very bad condition, which leads potentially to the extinction of a number of species on the Luxembourg territory (natur&ëmwelt 2020). Luxembourg is one of the most fragmented countries in Europe (Katsikis et al. 2020).

Figure 5. Fuel tourism results in petrol station strips along the border. This image shows petrol stations in Wasserbillig-Mertert.

Individualistic and fossil-fuelled lifestyles

Luxembourg draws commuters from an increasingly large area, and the car is still the favoured mode of transport (Durand et al. 2018), such that Luxembourg ranks 53rd in the world in terms of traffic congestion (TomTom 2020). In Luxembourg-City, residents lost on average 45 hours stuck in traffic in the year 2019 – up 30% from 2018 (Inrix 2020).

Due to the absence of a resolutely urban culture – none of the bigger "cities" of Luxembourg are urban in the sense of offering a diversified retail landscape – the population goes shopping in malls to a large extent. Many of those malls are located in the arterial roads in front of the cities and are organised in linear shopping strips with an accumulation of “decorated sheds” as in the Route d'Arlon or the Route de Beggen, or in areas close to the border such as the Route des Ardennes or Mont-Saint-Martin, where malls and retail warehouses line up. Some of these shopping malls – a model from the 1950s as an essential part of the car-friendly city – are located in central locations such as Luxembourg-City (Royal Hamilius), Differdange (Ob'Korn), which further exhausts the local shopping scene, or even in new urban developments such as Belval (Belval Plaza) or the Cloche d'Or (Cloche d'Or Shopping Centre), which ruled out the emergence of a diversified and small-scale retail landscape from the outset. Another complicating factor for local and alternative retail trade is the extremely high rents for ground floor zones in the cities (and also in the shopping malls), which often can only be afforded by international retail chains, which in turn boosts the import of goods. As a result, many inhabitants do their shopping in other cities, such as Trier and Metz, both of which have the same population size as Luxembourg-City, but have maintained a certain degree of urbanity that no longer exists in Luxembourg.

Figure 6. "Modernity - Loved, hated or ignored? / Enquête Kutter" (De Brabanter et al. 2020)

The extent to which Luxembourg's lifestyle is based on car use is apparent in the high automobile quota, which at 780 vehicles per 1,000 inhabitants (STATEC 2020e)[4] is also the highest in Europe. The high automobile quota is also related to the horizontal structure of the territory. About the same size as the neighbouring Saarland, which is considered to be a sprawled Land, Luxembourg has a lower population density of 242 inhabitants/km^2 compared to 384 inhabitants/km^2 in Saarland. Sprawl is also characteristic for Luxembourg and the population is quite unevenly distributed over the territory, for instance with high density in the South and low density in the North and a marked differential to the other neighbours (Grand-Est: 96 inhabitants/km^2 further declining and the most rural of all Belgian provinces, the Province de Luxembourg with 64 inhabitants/km^2).

Historically, regional planning and housing have hardly coordinated their efforts, and – like transport – are also located in different ministries. For example, half of all housing units are single-family houses, which are either detached or grouped together as terraced houses (STATEC 2020f). The high level of individual transport is reflected in a high proportion of individual architecture. As a consequence of this individualisation, Luxembourg is also a leader in terms of average residential area, which has risen steadily for many decades and currently stands at 53 m^2 per inhabitant – and is even higher for rural and suburban houses. This is not only an ecological problem, because in a sprawling configuration, a viable public transport network can only be guaranteed to a limited extent and therefore the distances to the essential activities of modern life – working, shopping, leisure, social infrastructure – are high. Even the average distance between home and secondary school in Luxembourg is 11 km. It is also a social problem in view of an ageing society, in which a disproportionate number of elderly people live in single-family homes. The building sector is Luxembourg's second largest source of CO_2

[4] This number includes 112 company cars used by cross-border commuter.
From our perspective looking at Luxembourg's functional area, deducting this share from the total number of cars registered in Luxembourg would result in a zero-sum-game as it would then have to be added to the statistics of the neighboring regions, which themselves already have comparably high rates of car ownership.

Figure 7. Sealed platform for a future petrol station next to Pontpierre on the A4.

emissions. In addition to the typological problem of low resident density in buildings, which not only increases distances but also facade surfaces, the building stock has a high consumption of energy and materials. Buildings in Luxembourg are predominantly heated by fossil energy and are constructed chiefly with materials high in embodied CO_2 emissions, such as reinforced concrete, steel, pumice, poroton and inorganic insulation materials. The design of the existing building stock is such that deconstruction for reuse or recycling is difficult. Buildings are still too often demolished rather than converted or overbuilt. A culture of the *As found* is lacking – the famous Smithson concept of the 1970s of approaching existing buildings cautiously without prejudice, which does not only concern an extraordinary building culture but generally the ordinary stock. The conceptual and material layout of existing buildings and the skyrocketing demand for real estate make it attractive to replace the existing stock with a larger and more modern building volume. Another problem is the lack of building gravel and sand, the overproduction of building rubble and excavation material mostly due to the construction of multi-layered underground garages. The disposal of these materials is reaching its limits and is now often deposited in landfills beyond the border.

Lack of autonomy, lack of resilience

The extent to which Luxembourg, as a relational country, is generally dependent on regional and international goods, capital and people is shown by the fact that the strong export of services is counterbalanced by strong imports, especially of goods and food: at 191% of GDP (as opposed to 29% of the OECD average – OECD 2020). Luxembourg's agricultural sector is dominated by meat and dairy production, which contributes 5.2% of national GHG emissions through methane and nitrous oxide emissions from enteric fermentation and manure management (Eurostat 2017). In meat production, Luxembourg produced 110% of its consumption needs in 2018 (STATEC 2020g). Even given Luxembourg's small size and climatic conditions, autonomy in fruit (12%) and vegetables (2%) is low compared to the EU-15 country average of 74% and 102%, respectively (Kolodziejczak 2018). To the same extent that Luxembourg's cities are not very urban, its countryside is not as productive as it could be. As a result, Luxembourg, as an originally agricultural country, has a deficit of resilience in terms of its food supply. For example, if lorries had been blocked at the borders during the pandemic, the local supermarkets would have had supplies for only another three days. Even though GHG emissions in Luxembourg are declining, emissions in the building sector and in agriculture have continued to rise.

Luxembourg is no less affected by climate change, for which it is proportionately more responsible than most other countries in the world: the country is experiencing the impact of climate change, with higher average annual temperatures and more frequent extreme weather events. Flash floods caused extensive damage and economic losses in 2016 and 2018; in August 2019, a tornado caused damage in the south-west of the country and temperatures reached 40.8°C (OECD 2020). Forest dieback can currently be observed everywhere. Compared to 1980, when 77% of all trees in the forest were in good phytosanitary condition, only 28% are in good condition today (König 2020). Many vineyards are struggling with the dry periods, late frost events, and heavy rainfall. Overall, reliable drinking water provision for residents is becoming an issue, not only because of increasingly frequent droughts, but also related to rapidly growing groundwater nitrification due to intensified agricultural practices. The average air temperature in Luxembourg in the period from 1981 to 2010 was 9.3°C (Meteolux 2020), which is 1.0°C warmer than in the period from 1961 to 1990 (MECDD 2020).[5] Climate projections for Luxembourg also show a further increase in air temperatures in the future, mainly due to an increase in minimum temperatures in the winter months (Alves & Junk 2020). The perception of many that climate change is only manifesting itself in distant countries and will only affect future generations is no longer true.

The drivers of GHG emissions are structurally tied to population and economic growth and cannot be controlled by cosmetic policies. Financing the strong social system of Luxembourg is dependent on continued economic growth. While the pension system in general and in particular for public employees is generous, the number of people employed in the public sector has increased steadily since the 1970s (STATEC 2020h). In order to finance these standards in the future, continued growth is pursued at the cost of seeking the decoupling effect of green growth. But to achieve

[5] For comparison: the global temperature increase has been only 0.85°C since 1880 (IPCC 2013).

the GHG reduction targets set, a more substantial transformation of the built and unbuilt environment is necessary as well as of the fossil energy-intensive lifestyles, including the emphasis on increasing wages and increasing consumption.

Multi-level governance challenges

First and foremost, thinking about governance challenges in the context of 'Luxembourg in Transition' requires a perspective that distinguishes between planning, building and urbanism ("spatial planning") on the one hand, and policy and politics as practiced in the country's institutional context on the other hand. Both are the driving forces that determine the ways in which the demand for space by various actors (private, public, economic, social) is being sorted out at the two levels of government: state and local. Secondly, in some contrast to this apparently clear division of labour and responsibilities nested in a two-tier system, we take into account the "blending" of spatial scales, that is, the mobilisation of resources and both the practice and absence of regulation at local, state and supra-national levels of government and governance (Affolderbach & Carr 2016). Without this clever politics of scale, the remarkable economic success and the associated socio-economic transition that Luxembourg has undergone in the recent past would not have been possible. This means to reflect upon the demand for development at global, greater regional and local scales altogether, and to adjust the related responses of actors respectively (Hesse & Wong 2020).

This leaves a rather complex picture of interdependent systems that determines any intended transition of the country and its neighbours towards a better future. This transition is neither local nor regional/cross-border alone, but it needs to be addressed at all three levels of scale as mentioned above. Also, any outlook into probable, desired or possible futures should get started with a brief look into the past: tying in with the historical conditions and pathways of the country's territorial evolution. Luxembourg represents a rather "young" case of planning and spatial governance. Effectively, there is little tradition on which today's strategies could refer to: For decades, regular town planning was entirely localised and in the hands of mayors and municipal councils, as planning and building sovereignty lies with the municipalities. Overarching orientation, guidelines or steering mechanisms were hardly existing until recently. Inter-municipal spatial planning was only institutionalised by law in 1999. However, effective, formally binding plans at the supra-local level simply do not exist or have been under preparation for more than a decade now, without coming to practice as yet. Also, in a country that has become successful in the shape of economic laissez-faire and minimum regulation, intervention by planning is politically controversial and contested.

That government regulations have been unable to curb development and settlement activities in recent times is not only due to the lack of (inter-municipal) binding rules and institutional mechanisms, but also associated with missing consensus and consistency between the two levels of decision-making: state and communes (Hesse 2015). Rather rarely can the two sides agree on major development corridors and practices, and if they do, then it is most likely state power that is set in place here (see e.g. the large-scale urban projects on Kirchberg and Belval). Moreover, roughly a third of the members of national parliament are local decision-makers at the same time (i.e. mayors, members of aldermen committees). This means that they are part of a discrete political negotiation system that permanently oscillates between local and national interests, stakeholders and the like. Civil society has rarely been involved in planning frames, prospects and (even more so) related decision making, which, if at all, has been changing only recently.

Last but not least, the rather unique trajectory of economic growth and wealth that has changed Luxembourg so visibly in recent times has put the country's land resources – to some extent a limited territory – under enormous pressure. Development dynamics, particularly in the capital city's agglomeration, were massive in their magnitude and occurred over a relatively short time span. The more the demand for development in general, and for office space in particular, grew, the more land reserves were allocated for development, the more building permits were issued. In the end, these changes have led land development and related policy to become part of a bargaining regime between property owners, development agents and local/state authority – providing a sort of globalisation dividend to land owners, which has to be paid for by the new arrivals on the housing and labour markets. It has thus turned Luxembourg's real estate market into one of the most expensive ones in Europe.

The practice of planning and development itself rests on complex legal, technical and politico-administrative procedures, which are difficult to fully comprehend and which, for their part, have repeatedly challenged governmental institutions in the past. In addition, this practice has contributed to hampering even those programmes, plans or developments that had previously reached a certain political consensus. This applies for example to large-scale urban projects such as the science city Belval, which due to its size and planning complexity was realised only with major delays and increased costs; it also applies to planning frameworks such as the national sector plans for settlement, transport, open space and economic activity zones, which were subject to political and juridical controversies between public and private stakeholders at all levels for a while and have therefore not yet been implemented. Moreover, speculative interests from private owners and private investors are likely to block the development of key urban development areas as well, which is

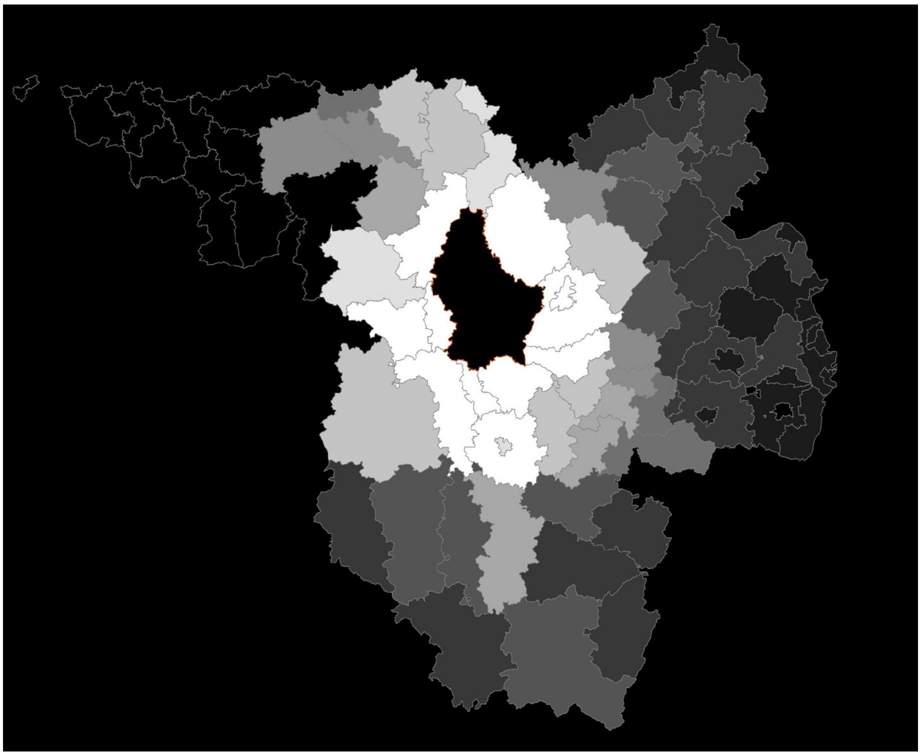


Figure 8. Luxembourg's commuters from the Greater Region in 2020.
A lighter colour indicates a highter density of commuters to Luxembourg.
The map shows Luxembourg's strong impact on the region.

demonstrated for instance by the capital city's Place de l'Etoile that was cleared of its old building structures approximately 15 years ago and has remained vacant ever since.

The high demand pressure as well as enormous profits offered by real estate valorisation are the driving forces of the development process, while the complexity and duration of planning "procedures" are the constraints that hinder implementation. Based on our own research experience, it can be argued that the country's planning system is both over-regulated and under-strategised (Leick et al. 2020; Becker et al. 2019; Hesse 2015). Therefore, 'Luxembourg in Transition' is particularly very timely in terms of spatial governance, as there is a need for strategic orientation to not only respond adequately to the external challenges mentioned in other sections of this report (such as climate change, environmental issues, the challenge of resilience), but also to address the range of problems that, as mentioned here, lie within the governance and planning system. Given the spatial imbalances and inequalities that are necessarily inscribed in Luxembourg's most powerful economic development trajectory, there is also a need to call for a more balanced development pattern, pursuing social, economic and thus spatial justice at all levels of politics and planning that are effective here. However, related ambitions have then to be balanced against the effectiveness and power constraints that spatial planning is usually confronted with – not exclusively, but also in the Grand Duchy of Luxembourg.

Figure 9. The dismantling of the city's fortifications, which began in 1867 with the breakthrough of the great avenues, such as the Avenue de Monterey, triggered a major paradigm shift in urban development. While the fortress was replaced by a green corridor, a dynamic urban expansion was initiated beyond the historic urban fabric.

Potentials, precedents and perspectives

In comparison to agglomerations, such as the Grand Paris or the Greater Moscow, which were the object of major prospective planning in the last decade, Luxembourg and its functional space is not a metropolis. And although it displays many similar phenomena to Geneva – high economic and demographic growth, a strong financial economy, many international institutions, a high standard of living, housing shortage, cross-border commuting – the functional space of Luxembourg itself is potentially a more manageable and more sparsely populated urban landscape than Greater Geneva. Ten years ago, the discourse of urbanism and territorial design was characterised by bigness in the form of metropolisation (some even raved about the megalopolises like NWEM and the Chinese mega-cities). This view is now retrograde, as today the local turn, medium-sized towns and cities as well as the rural and the *ländliche Verheissung* (Burke et al. 2019; AMO/Koolhaas 2020) are back in the focus of the discourse and seen as advantageous. For Ebenezer Howard, the ideal size of a garden city was 50,000 inhabitants, for Oswald Mathias Ungers the ideal size of a city 200,000. In contrast to the Grand, the Small seems to have more potential for the socio-ecological transition: on the one hand, because there is simply less material stock that needs to be converted and elements are added rather than demolished; on the other hand, because there is more open space that can now be used for the essential factors of ecological transformation: forests, water areas, air corridors, and organic farming. With its low density the functional space of Luxembourg contains the DNA of a potentially balanced city-landscape between, on the one hand, some built areas that could be densified, diversified, intensified and thus turned into urban neighbourhoods, and, on the other hand, many unbuilt areas that only have to be reconfigured.

In recent years a number of initiatives have merged across sectors, aligning their action around the Sustainable Development Goals agenda – as shown on the website aktioun-nohaltegkeet.lu or in the movie Eng Äerd. The so-called Rifkin study (Rifkin et al. 2016), despite falling short on a number of crucial aspects (including spatial/social justice, wealth distribution, and regional circularity and resilience), has produced a number of important impulses around circular economy, electromobility and renewables. More recently there are promising projects such as 2000 m^2 for our food (2018-2022), which demonstrates the possibility of feeding oneself sustainably based on local food and highlights the relationships between our dietary habits, agriculture and environmental protection (2000m2 2020). SustEATable, an integrated analysis of dietary patterns and agricultural practices for sustainable food systems in Luxembourg (2018-2022), is another project that assesses holistically the current sustainability level of the Luxembourgish agriculture sector using the SMART (Sustainability Monitoring and Assessment RouTine) Farm Tool. Other aims include to identify necessary changes to dietary patterns and production practices, and to develop differentiated strategies for the development of sustainable food systems in Luxembourg. In the first phase of the project farms are assessed for their achievement of the SAFA (Sustainability Assessment of Food and Agriculture system) sustainability goals outlined by the Food and Agriculture Organization of the United Nations (FAO 2014).

Another positive example which offers the bottom-up groundwork for a socio-ecological transition is the rise of the citizen-based Transition movement (Hopkins 2011) also in Luxembourg. Since the creation of the Centre for Ecological Learning Luxembourg (CELL) in 2010, the "Transition Luxembourg" network now includes several regional groups on food, energy, economy, community gardens; several cooperatives including TERRA on community supported agriculture, TM EnerCoop on community owned renewable power and AlterCoop on prosumer food systems; as well as numerous projects including an Earthship autonomous building in Redange, a Transition House in Esch, a REconomy network developing new forms of economy embedded in community needs. Such initiatives, initiated and supported by citizens, have an enormous potential to test the “less is more” narrative in practice and apply and share solutions according to the motto "think global, act local". In recent times, such community-led initiatives have gained much experience. They have professionalised, created jobs and a growing number of new transition projects, collaborating with municipalities, national platforms and European networks (Ecolise 2020). CELL has for instance been mandated by the Ministry of Environment (MECDD) to help local authorities and other stakeholders to decarbonize their communities and make them more resilient, and to give them the drive to move beyond the “low hanging fruit” of local decarbonisation. In order to reach the Paris agreement climate goals, all available forces are needed at the local level: from civil engineers to citizen groups, from technicians to community builders and eco-entrepreneurs. The community-led initiatives have also evolved or adapted methodologies for facilitating engaging cross-sector dialogues and collective participatory transition activities.

The Grand Duchy has undergone a series of successful socio-economic transformations in the course of the 20^{th} century (which are always also spatial transformations): from the rural to the industrial, from the industrial to banking, from banking to the financial service and tech industry. Strategies for an ecological, resilient future should build upon this tradition of successful adaptation to the challenges of an ever-changing international context and mobilise all available forces at the local level: from civil engineers to citizen groups, from technicians to community builders and eco-entrepreneurs.

II. METRICS

01 Metric Framework: Decarbonising in a Resilient Way

Objective function and set of constraints: Resilient decarbonisation

The main objective of our prospect is to minimise GHG emissions per capita per year to a level that is sustainable and in keeping with the climate warming targets set in the Paris Agreement. The GHG or carbon footprint of the average Luxembourger is currently around 13 tons of CO_2 eq. capita^{-1} year^{-1}, while emissions would need to remain below 1.6 tons of CO_2eq. capita^{-1} year^{-1} to stay well below the 2°C warming scenario of the Paris Agreement (O'Neill et al. 2018). Reducing GHG emissions by almost 90% is an enormous task that will affect almost every aspect of our lives. Focusing on the resident's footprint does not mean that we exclude the rest of Luxembourg's production-based emissions (industry and exports, and non-resident emissions) – we choose this target as it aligns with the scope used to set the 1.6 t target, as well as that of other indicators.

We take a life-cycle approach, i.e. we measure GHG emissions embodied in the goods consumed by Luxembourgers, independently of whether these emissions were generated in Luxembourg or abroad. We do not minimise total GHG emissions, and instead focus on GHG emissions per person, because Luxembourg's predicted increase in population is driven by net immigration rather than natural increase. Since GHG emissions are a global and long-term issue that affects more than our local environment or generation, we feel justified in framing our objective in this way.

In this report, we document how Luxembourg can move from 13 to 1.6 tons of CO_2 eq capita^{-1} year^{-1}. While this reduction in GHG emissions is the driving force and principal goal of our research and our proposal, we explicitly commit to assessing the impact of the required interventions on other environmental and social dimensions. These form a constraint on the type of interventions we can impose and serve to make the decarbonisation path resilient in the ecological and social dimensions. We take this stand because changes in production, consumption, and behaviour are costly and require a large collective effort and a transition of this scale is to a large extent non-reversible. Embarking on a transition path that is inherently unsustainable in terms of our impact on other environmental resources or on human health would require a reset at a later stage when we encroach upon the limits along those sustainability dimensions. Ultimately, reducing GHG emissions is a goal that is in service to maintaining the wellbeing of humanity and the environment for generations to come.

We selected a set of resilience indicators based on the state of the art of sustainability assessment, ensuring that indicators measure end-point rather than intermediate effects, and that the set of indicators has minimal overlap with maximal coverage across sustainability or resilience dimensions. The most limiting factor for our selection of indicators was our ability to associate decarbonisation interventions with changes in the environmental and social indicators. It is one thing to monitor the sustainability status of Luxembourg and another thing to determine how the sustainability indicators change in response to certain decarbonisation interventions.

Environmental boundaries								
Domain	**Indicator unit**	**Status 2020**			**Max / ceiling 2050**	**Scope**	**Area**	**Calculation**
		Production (from LU)	**Consumption (in LU)**	**Consumption (by LU res)**				
GHG emissions	t CO_2eq cap^{-1} yr^{-1}	17	26	13	1.6	life-cycle	global	EXIOBASE
Marine eutrophication	kg N cap^{-1} yr^{-1}	5.6	39	20	8.9	life-cycle	global	EXIOBASE
Freshwater eutrophication	kg P cap^{-1} yr^{-1}	9.8	23	12	0.89	life-cycle	global	EXIOBASE
Bluewater use	m^3 cap^{-1} yr^{-1}	103	583	292	574	life-cycle	global	EXIOBASE
Air pollution	DALY $(10^3$ cap$)^{-1}$ yr^{-1}	14	21	11	1.0	life-cycle	global	EXIOBASE
Material use	t cap^{-1} yr^{-1}	0	32	16	7.2	life-cycle	global	EXIOBASE

Social and environmental foundation						
Domain	**Indicator unit**	**Status 2020***	**Min / foundation 2050**	**Scope**	**Area**	**Calculation**
Climate regulation (CU)	t CO_2 uptake yr^{-1}	0.39	1.6	direct	LU	LIST, Othoniel et al. (2019)
Biodiversity (B)	median % achievement SMART	52	80	direct	LU	IBLA, SMART indicator
Unbuilt land (UL)	km^2 unsealed area	2246	2246	direct	LU	CORINE land cover
Life satisfaction (LS)	Lux Index of Wellbeing (base 100 in 2010)	101	101	direct	LU	LIST w/ Statec support, qualitative
Social justice (SJ)	Income quintile share ratio after transfers (S80/S20 ratio)	5.4	3.8	direct	LU, GR	Qualitative

Table 1. Environmental boundaries and social/environmental foundation
Note: GR - Greater Region.
*Climate regulation, life satisfaction, and social justice values are from 2019, unbuilt land from 2018, biodiversity from 2017. Sources for status and targets are described in main text.

Ultimately, we selected the indicators presented in Table 1, guided by our own experience in life-cycle sustainability assessment and by the "Doughnut Economics" model of planetary and social boundaries (Raworth 2017). Each indicator along with its target represents a constraint we impose on our objective of minimising GHG emissions per capita. In some cases the target is a ceiling (maximum) and in others a foundation (minimum). The constraints are not strictly binding, in the sense that, if necessary for our decarbonisation objective, we will include decarbonisation interventions that may cause us to fail to meet an environmental or social constraint. However, in setting up our objective function in this way, we can show explicitly to what extent decarbonisation within these ecological and social resilience bounds is possible.

We will calculate the impacts of our proposed interventions on the environmental boundaries listed in Table 1 using the environmentally extended, multi-regional input-output data, EXIOBASE (Stadler et al. 2018), in order to take into account life-cycle impacts of Luxembourgers' consumption of goods and services. Estimating the impact of our interventions on the indicators in the social and environmental foundation is more challenging and detailed further below. We note here that quantification of impacts is not always possible and may be substituted with a qualitative description. In addition, we calculate the impacts of some interventions only on a subset of the most relevant indicators.

Indicators, 2020 status, and targets

Conventionally, GHG emissions are primarily accounted for with a territorial approach, whereby national inventories of imported fossil fuels, agricultural processes, and land use are compiled to calculate the production-based emissions. This is shown in the first column of Table 1. In highly-globalised or smaller countries, this approach may not be as representative of the actual consumption-based emissions, otherwise known as "footprint", of the residents. For example, Switzerland in net terms imports the equivalent of twice its production-based emissions every year, whereas China or India are net exporters of GHG emissions, as they sell abroad more embodied carbon than their population uses (Ritchie 2019). Consumption-based emissions are shown in the second column of Table 1. In the case of Luxembourg, this approach is still not entirely satisfying, as 200,000 cross-border commuters technically "consume" in the Grand Duchy every day. Resident-only emissions are therefore shown in the third column of Table 1.

Aside from GHG emissions, we measure marine and freshwater eutrophication, respectively in kg N and kg P per capita,[6] as well as blue water withdrawal (fresh surface water used for human activities) embodied in final consumption. Phosphorus (P) emissions are costly to society for two reasons, because they contribute to freshwater eutrophication and because the majority of phosphorus for mineral P fertilisers is mined with global deposits rapidly depleting (Alewell et al. 2020). The air pollution indicator combines the amount of nitrogen oxides, sulphur oxides, and particulate matter emissions (2.5 μm) and converts these into a single indicator measured in disability-adjusted life years (DALYs), based on the toxicity model developed by Fantke (2016).

Finally, material use is also accounted for, as the lump sum of all materials extracted from nature annually to meet the final demand of Luxembourgers. This indicator measures the resource sustainability of conventional lifestyles, which currently lack circular economy solutions at scale (Hoekstra & Wiedmann 2014). As materials in this indicator are uncharacterised, it is biased towards material-intensive activities such as construction, and does not take into account the criticality of certain specialty metals or precious ores; these aspects will however be addressed qualitatively.

Mitigating climate change does not only depend on the strategies to reduce GHG emissions embodied in the goods and services we consume. It also depends on the capacity of ecosystems to capture CO_2. We set an ambitious target for carbon uptake in 2050, which is to fully match

[6] Nitrogen is the critical limiting factor to algal growth and eutrophication in coastal marine waters, phosphorus plays the same role in the case of freshwater.

the amount of GHG emissions to achieve net zero emissions including the impact of land use, land use change, and forestry (LULUCF). Forests, and to a lesser extent grasslands, are those ecosystems where carbon sequestration flows may increase on a yearly basis, while croplands, wetlands and other natural or semi-natural ecosystem types either marginally contribute to increased carbon sequestration rates or provide a zero balance between carbon storage and release. Moreover, efforts to increase green areas in cities and include nature-based solutions in built-up land can be put in place to increase the global climate regulation service.

Data used for the calculation of current annual carbon sequestration were extracted from the VALUES model for Luxembourg (https://www.lifecycle-values.lu/ – Othoniel 2019), which includes projections of carbon sequestration rates for woodland composed principally by four species: spruce (~35%), beech (~42%), pine (~3%) and oak (~20%). According to the modelling outputs, the carbon sequestration flows (i.e. carbon captured and stored on an yearly basis) corresponds to ~1.03 tons of C (= ~3.8 tons of CO_2) ha^{-1} $year^{-1}$. This represents ~380 kt CO_2 sequestered every year from the forest areas in Luxembourg (~101,000 ha). Whereas in the case of grasslands, the model returns an average carbon sequestration rate of ~15.5 kg of C (= ~0.06 tons of CO_2) ha^{-1} $year^{-1}$ or a total of ~2.2 kt CO_2 sequestered every year from the grassland areas in Luxembourg (~43,000 ha). Considering these estimations, for Luxembourg to reach carbon neutrality by 2050, which means capturing at least 1 Mt CO_2 per year, forest areas (representing the most performing ecosystems in sequestering carbon) should increase by ~1.6 times. Such an increase, which corresponds to an additional supply of C sequestration capacity equal to around 62% compared to nowadays, would correspond to a total forest area of around 2,600 km^2, i.e. approximately the current surface area of the country. In other words, if Luxembourg were completely covered by woodland, it could compensate for the expected 1 Mt CO_2 emissions in 2050.

The biodiversity indicator is a comprehensive assessment of agriculture's impacts on biodiversity, based on the Biodiversity Theme of the SMART-Farm Tool, V5.0 consisting of three sub-themes (Ecosystem Diversity, Species Diversity and Genetic Diversity) and 75 underlying indicators. This sustainability assessment method is based on the SAFA-Guidelines of the Food and Agriculture Organisation (FAO 2014; Schader 2016). The specific Biodiversity theme goal as defined in the SAFA-Guidelines is that "the areas under agriculture, forestry and fisheries are managed sustainably, ensuring conservation of all forms of biodiversity" (FAO 2014). Indicators in the SMART-Farm Tool that are used to measure goal achievement in this theme cover a wide range of practices and areas of agricultural production that have known effects on biodiversity, e.g. GMO-feedstuff, pesticide use, crop diversity, animal husbandry breed diversity, implementation of agroforestry systems, measures to prevent soil degradation and improve soil fertility, and areas and measures in place to promote biodiversity. In the project SustEATab, the SMART-Farm Tool was used to assess the sustainability performance of 87 farms in Luxembourg and showed a median goal achievement in the Biodiversity theme of 52%. We target to increase this to a minimum of 80% goal achievement by implementing beneficial agricultural practices that promote biodiversity while also reducing GHG emissions and increasing carbon uptake. Limiting the applicability of the indicator only to the agriculture sector is a drawback, since other activities affect biodiversity. However, since agriculture is one of the main forms of interaction of the economy with nature, the benefit of being specific in this area outweighs the limitation in scope.

The anticipated population growth for Luxembourg increases the pressure on land use for the residential sector. The result of the population increase in the past decade has been an increase in the amount of land that is sealed, which can be considered an essentially irreversible process. Soil sealing results in the loss of soil biodiversity and an increase in flood risk. The EC Roadmap to a Resource Efficient Europe (COM(2911) 571) sets a target of no net land take by 2050. Our target for 2050 is to not exceed the current level of soil sealing, or conversely maintain the current level of unsealed land, despite the expected population increase.

The life satisfaction indicator is based on the PIBien-être 2020 report, for which STATEC constructed a Luxembourg Index of Wellbeing to aggregate 22 indicators on employment, income, work-life balance, housing, health, education, governance, environment, security, and self-reported life satisfaction. We can measure the impact on our interventions on one or more of these underlying indicators, and with STATEC support, obtain the overall effect of the intervention on life satisfaction. We set as a minimum target for 2050 to maintain the current level of life satisfaction in Luxembourg. We expect life satisfaction to generally improve given that particulate emissions and pollution in general, which are set to decrease in our system, are themselves determinants of life satisfaction and that we propose a set of interventions aimed specifically at improving life satisfaction and social justice, for instance by reducing average commuting time. Given this expectation we could set a higher target for 2050, but we expect some of our interventions to have a negative effect on life satisfaction, at least in the initial phase of changing habits, such as the inconvenience of switching from private to public transport or the reduction of meat in the diet.

Finally, we selected the income quintile ratio of S80/S20 after transfers as an indicator for social justice and equality. We track this indicator not only in Luxembourg but also in the Greater Region to measure regional disparities. High income inequality reduces society's capacity for resilience. The COVID-19 pandemic is one such example. Mitigating the spread of disease required everyone to change their lifestyle, but income inequality may have prevented some from taking adequate safety measures to protect public health: Greater income inequality was found to be associated with COVID-19 mortality (Elgar et al. 2020). The target of 3.8 is linked to the 10th Sustainable Development Goal of reduced inequalities (Indicators 2020).

Presenting the results: Doughnut model, Ecological Footprint, ISEW

Our main graphic of interest is Luxembourg's progress on the decarbonisation timeline, i.e. a waterfall chart showing gradual reductions in GHG emissions from the 2020 level of 13 t CO_2eq capita^{-1} year^{-1} to 1.6 in 2050. We present our results using other visualisations as well. The target we have set for decarbonisation alongside the constraints for other environmental and social indicators mean that progress in these domains can be visually presented using the Doughnut Model of social and planetary boundaries developed by Raworth (Raworth 2017). We have designed a doughnut graphic for Luxembourg (fig. 10) based on Luxembourg's 2020 status (in terms of resident, consumption-based per-capita) presented in Table 1. The Doughnut graphic is particularly apt at capturing the goal of resilience, since it shows Luxembourg's status in relation to social and planetary boundaries in multiple dimensions. The Ecological Footprint and the Index of Sustainable Economic Welfare methods convert Luxembourg's impact on environmental (and social) dimensions into a single indicator – global hectares in the case of the EF and euros in the case of ISEW.

The Ecological Footprint is an accounting system to track the amount of biologically productive land and water that is required by a country to produce the natural resources it consumes and to absorb the emissions it generates. The Ecological Footprint tracks back all the demands that compete for biologically productive surfaces, such as sequestration of CO_2 from fossil fuel combustion and the production of food, fibre, timber and energy. Biocapacity is the ability of ecosystems to renew biomass. Both Ecological Footprint and Biocapacity are traced back and compared based on two principles: (a) by adding up all the competing demands on biologically productive surfaces and (b) by scaling the areas proportionally to their biological productivity. The scaled areas are called global hectares (gha) and are defined as biologically productive hectares with world average productivity.

The areas are not necessarily located in the assessed country and can be imported in the form of resources from anywhere in the world. In 2018, Luxembourg with an area of 258,600 ha provided 802,000 gha, as the productivity of its land is higher than the world's average (Keßler et al. 2020). However, Luxembourg consumed in the same year 7,625,000 gha, corresponding to 12.7 gha/inhabitant, to cover its needs. About 8% of the ecological footprint of consumption is attributable to the crop footprint, 5 % to grazing footprint, 11% to forest products footprint, 1 % to fish footprint, 1 % to built-up footprint and a total of 74 % to the carbon footprint. In turn 30 % of the carbon footprint in 2018 was due to fuel consumption by non-residents, so-called fuel tourism. The footprint of food consumption added up to 2.1 gha/inhabitant, of which almost 60 % are used for fish (9 %) and food of animal origin (50 %).

The Index of Sustainable Economic Welfare (ISEW), like the Genuine Progress Indicator (GPI) or other similar indices, are macroeconomic metrics that help to go beyond the use of conventional GDP, considering additional aspects of the environmental-social-economic nexus that better characterise the concept of sustainability (Daly et al. 1989; Cobb et al. 1995). For example, items not taken into account by the GDP like non-paid domestic labour and a certain amount of public expenditures, perceived as

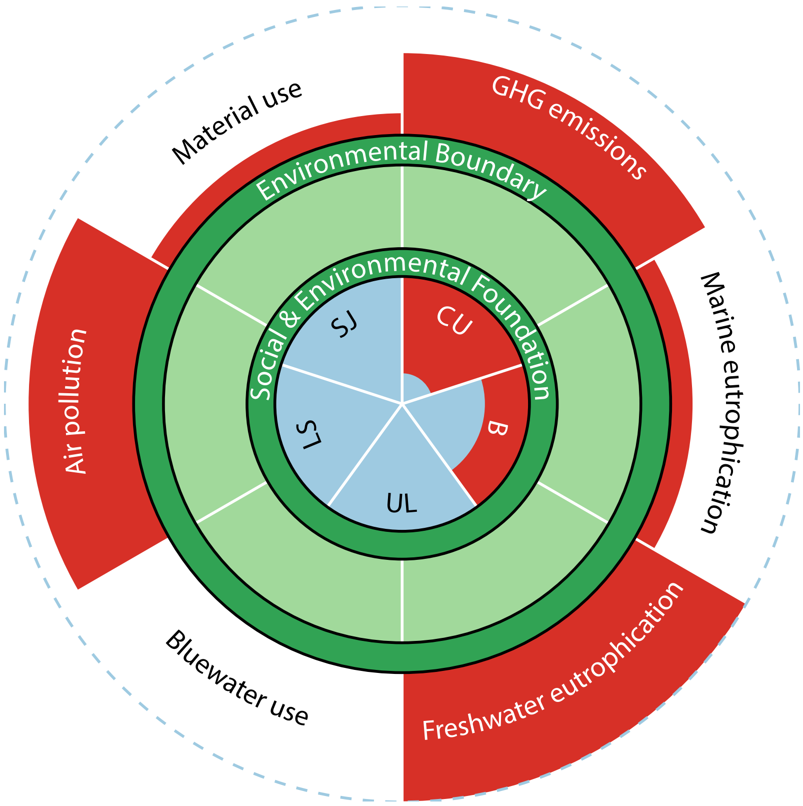


Figure 10. Luxembourg's 2020 status in terms of environmental boundaries and social and environmental foundation. CU - carbon uptake, B - biodiversity, SJ - social justice, LS - life satisfaction, UL - unbuilt land. A red area represents an overshoot from the ceiling (for environmental boundaries) or a failure to meet a threshold (for social foundations). E.g. bluewater use is deemed sustainable, as it is under the ceiling, while freshwater eutrophication is the indicator that overshoots its boundary by the highest margin. Designed by LIST and based on Luxembourg's 2020 status and the 2050 targets detailed in Table 1 (p. 20)

enhancing welfare, are added to obtain the final ISEW scores, while items like defensive expenditures, both public and private, and environmental costs (e.g. pollution, GHGs, non-renewable resource depletion) and social costs (e.g. commuting time, noise pollution) are deducted. As a result, literature on country historical time-series analyses shows that the ISEW typically grows in parallel with GDP up to a point – in many cases occurring during the seventies, beyond which it stagnates or decreases due to pressure factors affecting the social and the environmental spheres i.e. the so-called "threshold hypothesis" (Max-Neef 1995; Niccolucci et al. 2007).

The ISEW was recently quantified for the Grand Duchy of Luxembourg, starting from 1960 and projecting the evolution of the indicator until 2030 according to different energy consumption scenarios (Rugani et al. 2018). In compliance with previous evidence from the ISEW literature, results for Luxembourg confirm that relying on alternative measures to GDP contradict the hypothesis that economic growth necessarily increases welfare. More specifically for the 2020-30 period, the Luxembourgish ISEW would grow over time at a much slower pace than GDP, mostly due to increases in defensive expenditures (in particular with regard to the costs for mitigating the long-term environmental damage due to historical carbon emissions in Luxembourg). As a consequence, the historical annual average values of ISEW are around 73% lower than GDP. This gap may decline in the future by implementing the current EU agreements on renewable energy targets, providing a slight but tangible recovery of the economic welfare over the next 10 years. A new estimation of the ISEW based on the constraints proposed here can certainly help understanding if and how other social, environmental and economic factors can play a role to reach the environmental and social targets fixed in the present study.

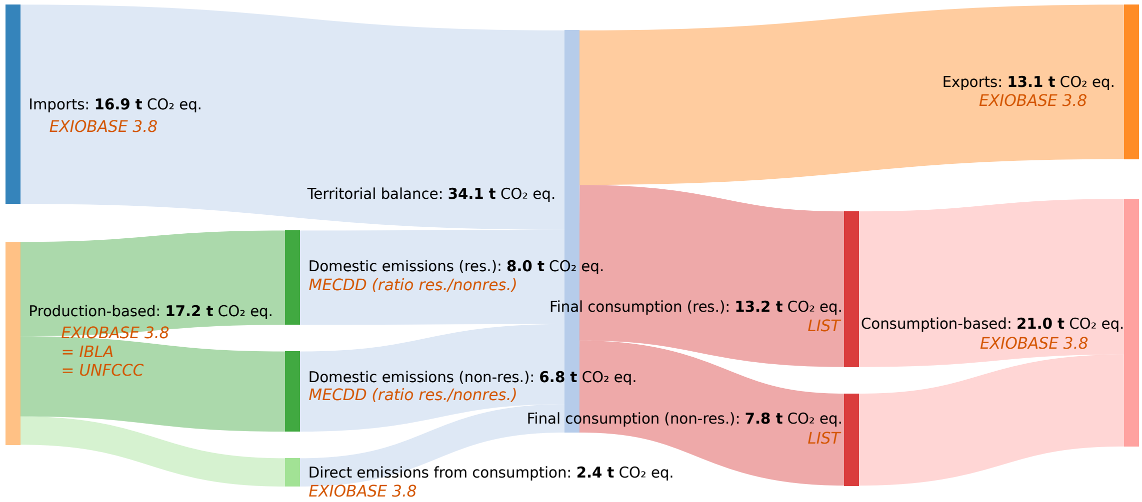


Figure 11. Sankey diagram of emissions of greenhouse gases embodied in imports, domestic production, exports, and final consumption, split into resident and non-resident shares. All flows are in t CO_2 eq. per resident in 2018. Sources are indicated in orange. Discrepancies between accounting frameworks remain, and will be addressed in Stage 2.

Area of interest: global, regional, national, local, cross-border

Our environmental ceiling indicators are all measured at the global level from our estimation of the life-cycle environmental impact of Luxembourgers' consumption. We choose this scope to evaluate decarbonisation interventions, but we also keep track of the GHG emissions linked with non-resident consumption and production in Luxembourg (including exports), as Luxembourg has an influence on these carbon flows (see the various scopes in figure 11). In contrast, our indicators for the social and environmental foundation are measured for Luxembourg or the Greater Region only and include only direct or non-life-cycle impacts. In Stage 2, we will elaborate on the role that coordination across the Greater Region plays in ensuring a more rapid decarbonisation transition. Here we plan on focusing on cross-border commuters and decarbonising the transportation system of the Greater Region. We will also address issues in spatial justice and social justice more broadly that arise in particular from certain interventions, such as the much reduced residential area per resident available in our proposed buildings (with a new emphasis on shared spaces) that stand in the much reduced residential area per resident on offer in our proposed buildings created according to our transition principles that stand in contrast to larger, existing residential units and estates.

Assumptions for our metric framework

We calculate the impact of our interventions based on several assumptions detailed in Table 2. We use STATEC's estimated population growth to 2050, medium scenario (1.5% annual growth), and include a set of constraints around imports in our objective statement. Notably, we restrict imports to not exceed the current share. Finally, we explicitly account for decarbonisation occurring over time in other countries, which appear in our calculations as the life-cycle, global emissions embodied in the goods and services consumed by Luxembourgers. In particular, we assume a decarbonisation rate that matches the decarbonisation path we have prescribed to Luxembourg (from 13 to 1.6 tons of CO_2 eq capita^{-1} year^{-1}), which translates to an effective annual decarbonisation rate of 6.8 percent. For electricity consumed in Luxembourg, we assume that our neighbouring electricity grids decarbonise according to those countries' projections as detailed in Table 2.

Assumptions	Unit	Description	2020	2030	2040	2050
Population	# people	growth based on STATEC projections	626031	759000	874000	966000
Share of energy imports	%		Do not exceed current share			
Share of food imports	%		Do not exceed current share			
Share of consumption imports	%		Do not exceed current share			
Rest of the world's progress on transition	% reduction in tons CO_2 eq. / process relative to 2020 level	For life-cycle assessment, global scale	Assume a 6.8% annual decarbonisation rate			
Germany's avg electricity mix	g CO_2 eq./kWh	EC PRIMES model (current policies), ecoinvent 3.6* factors	649	430	264	126
France's avg electricity mix	g CO_2 eq./kWh		108	43.5	34.5	35.2
Belgium's avg electricity mix	g CO_2 eq./kWh		170	263	271	213

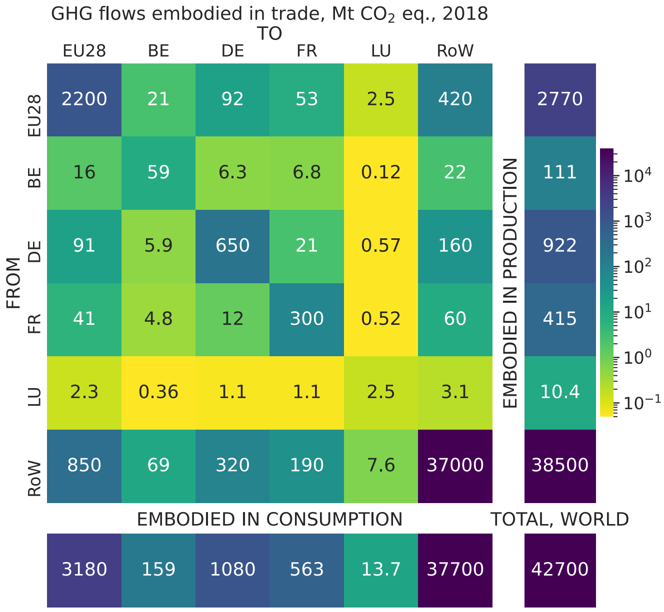
Table 2. Assumptions for calculating the impacts of interventions

Approach

The overall approach is to select interventions that move Luxembourg along the decarbonisation path to meet the 1.6 t CO_2 eq capita^{-1} year^{-1} in 2050 while remaining within our set of ecological and social constraints. Most of our interventions rely on existing or proven technologies, for which we can be relatively certain about the achievable reduction in GHG emissions. In presenting the decarbonisation path, we distinguish between solutions with a known, quantifiable effect and those with more uncertain effects on GHG emissions. We also ensure that our interventions are coherent across sectors and together offer a systemic approach to resilient decarbonisation. Overall, the exercise of selecting interventions includes elements of both forecasting and backcasting and is highly iterative: the actual selection of interventions and the “amount” of each intervention is influenced by our vision for the future and what we think is feasible both in terms of technology and individuals' willingness to accept changes to their current lifestyle. Thus, while the selection of interventions has more of a design element to it, the impact calculation of these interventions is scientifically rigorous both in terms of methodology and scope as we rely on life-cycle sustainability assessment according to ISO standard 14044:2006.

There are many ways to decarbonise and while most paths share common elements, individuals likely prefer different interventions with similar reductions in GHG emissions but different effects on their current way of life. In Stage 2 of developing our proposal, we will conduct focus group sessions to elicit consumer preferences on the preferred approach to decarbonisation. Our focus group sessions will focus on different options for residential living spaces that generally feature a reduced area in individual apartment units but increased common areas. The sessions will also address teleworking in shared co-working spaces close to residences. In addition, we specifically include participants from neighbouring countries next to Luxembourg residents to address questions in public transportation with a particular focus on cross-border commuting options. Finally, the sessions will also focus on consumers' preferences for diets that feature a reduction in embodied GHG emissions and are generally characterised by a reduction in meat and increase in local or seasonal produce.

* (Wernet et al. 2016) This database is also the source used by the Institut Luxembourgeois de Régulation to determine the direct CO_2 emissions of electricity products, however here life-cycle GHG factors and transmission losses are accounted for, which explains potentially higher values. Calculation details are available in (EC 2020).



02 Decarbonisation Pathway: The Ecological Transition of the Luxembourg Region

Figure 12. Emissions of greenhouse gases embodied in trade (off-diagonal), and domestic (diagonal), for Luxembourg, its neighbouring countries, rest of EU, and rest of the world. Calculations by LIST with EXIOBASE 3.8 for year 2018.
Reading: Luxembourg's territorial emissions in 2018 were 10.4 Mt, of which 3.1 is embodied in products exported outside the EU (e.g. steel). Luxembourg imported 7.6 Mt of embodied emissions from non-EU products (e.g. Russian oil for heating), and 0.6 Mt from Germany (e.g. automobiles). Worldwide emissions in 2018 were 42.7 Gt CO_2 eq.

Our starting point: The 2020 GHG footprint of the average Luxembourg resident

GHG footprinting can be performed in various ways, as the scope of GHGs and especially activities may vary widely. We differentiate here production-based from consumption-based accounting, further divided into a top-down and a bottom-up approach. Production-based accounting is based on the national inventory of GHGs, calculated from the consumption of fossil fuels and other processes within the borders of Luxembourg, which equalled 10.5 Mt CO_2 eq. in 2018 (Fourth Biennial Report 2020). Whereas this approach is used in international negotiations and reporting to the UNFCCC, we acknowledge the particular situation of Luxembourg as an interdependent territory with an influence that radiates beyond its borders by using instead a consumption-based approach. This perspective lets us adjust territorial emissions with GHGs embodied in trade, imports and exports. Using the multiregional input-output database EXIOBASE3.8 (Stadler et al. 2020), we illustrate in figure 12 the difference between the two: production-based accounts amount to 10.4 Mt,[7] while consumption-based emissions total 13.7 Mt.

Luxembourg hosts a disproportionate amount of industry relative to its size, and therefore re-exports a large quantity of embodied energy and carbon emissions. Based on the EXIOBASE3.8 database we estimate that only 2.5 Mt of CO_2 eq. are emitted in Luxembourg for Luxembourgers' final consumption (see the LU-LU cell in figure 12). Another 11.2 Mt is embodied in final consumption (e.g. extraction of oil in Russia for heating fuel oil consumption, or embodied emissions from the production of imported German motor vehicles). Including non-combustion greenhouse gases,

[7] The difference of 0.1 Mt with the UNFCCC reported value is due to statistical errors.

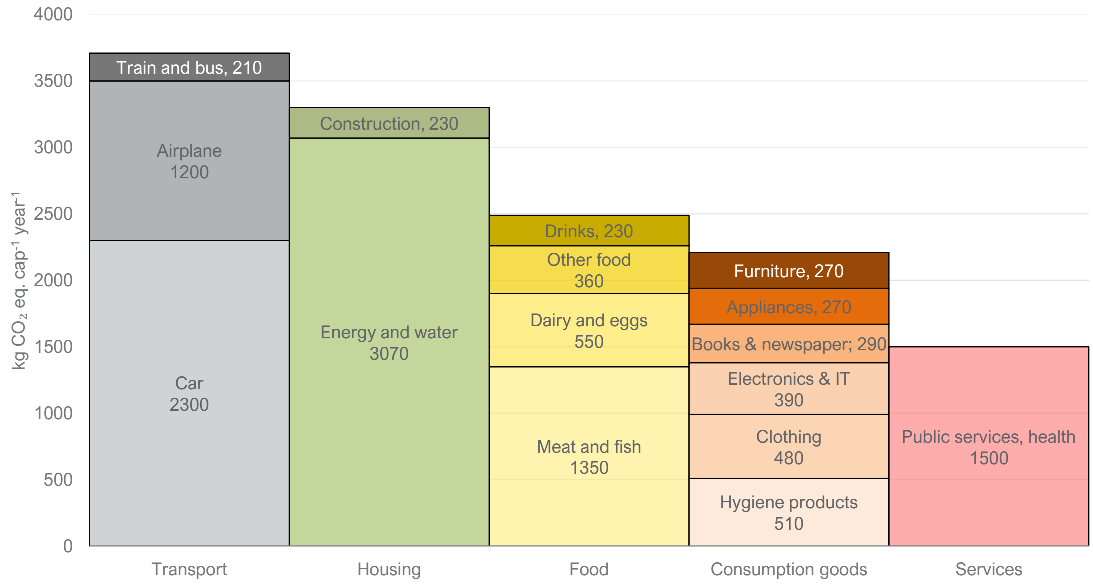


Figure 13. Carbon footprint of an average Luxembourger in 2019, by consumption category. Total 13.2 t CO_2 eq. capita^{-1} year^{-1}

for example methane and nitrous oxide from agriculture, the total footprint of Luxembourg is about 13.7 Mt CO_2 eq. in 2018. Territorial emissions, corresponding to the total emissions within Luxembourg's borders, on the other hand, amount to about 10.4 Mt CO_2 eq.

However, as we seek to calculate a per-capita footprint for residents, a top-down consumption-based calculation is still not satisfactory: residents only represent a small share of electricity consumption or fuel use (due to fuel tourism and cross-border commuters). So what is the "right" perspective? We choose a bottom-up approach, whereby every household consumption category is analysed and characterised in terms of life-cycle GHG emissions. The total amounts to 13.2 t CO_2 eq. per Luxembourgish resident in 2019; the detail of categories is shown in figure 13.

Transport is the main contributor, as car use dominates mobility in Luxembourg, and residents travel regularly by plane. Train and bus only constitute a small share of the footprint: their use is not yet widespread, and their per-passenger impact is low. Next, housing contributes 25%, mostly through energy use for heating and appliances (more than 1 Mt of emissions in Luxembourg originate solely from fuel oil and gas for residential heating – 10% of national emissions). Food impacts are also high, as Luxembourgers consume 86 kg of meat per person annually, of which 15 kg is beef – a GHG-intensive food item (Sala & Castellani 2019). The next category is consumption goods, including hygiene products, clothes, IT, and books, whose fabrication, transport and/or use require energy and generate emissions. Finally, public services, including education, research, healthcare, police, and administration account for about 1.5 tons per resident. Each of these categories surpasses today the target set for a sustainable and resilient Luxembourg by 2050, showing the daunting task ahead. However, the exercise is instrumental for setting priorities for the next *chantiers* to come.

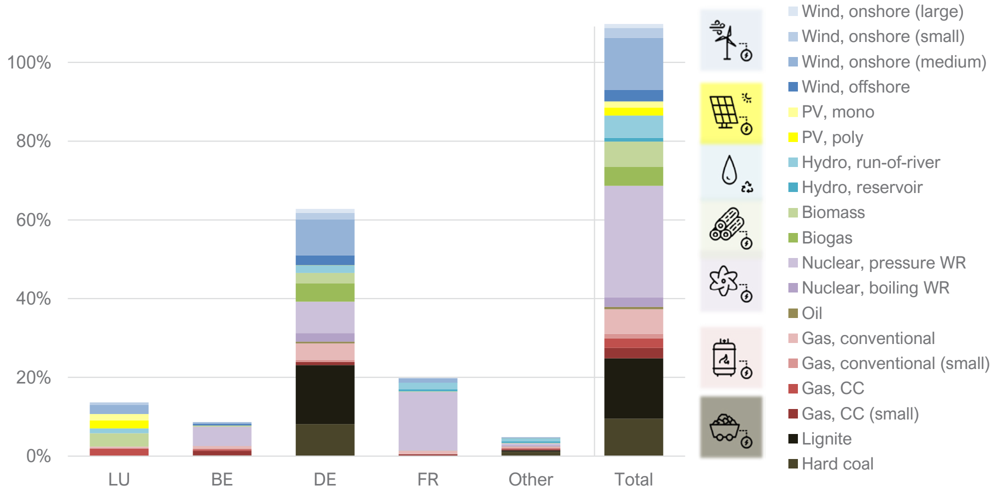


Figure 14. Luxembourg electricity consumption in 2019, by source and country of origin. The total surpasses 100% because of losses in the network and the small share of electricity used in pumping storage.

Luxembourg's energy landscape in 2020

Luxembourg's energy landscape is a good illustration of the degree of interdependence it entertains with neighbouring countries. In 2019 the Grand Duchy produced no more than 15.9% of its total electricity consumption of 6.6 TWh, as shown in figure 14, corresponding more or less to the share of residential consumption (14.6%), with the rest used by commercial activities as well as heavy industries (Institut Luxembourgeois de Régulation 2020). As a result, most of the electricity is imported from neighbouring countries, which follow very different decarbonisation pathways: Belgium has vowed to close its nuclear reactors and to rely increasingly on natural gas, and France will most likely pursue its nuclear programme complemented by more renewables. Germany is slowly decarbonising by phasing out coal power, completely by 2038 (Moore et al. 2020). Additionally, 4.6 million tons of oil equivalent (42 TWh) of fuels are imported annually by Luxembourg, mostly to meet the demand of long-distance trucks and airplanes, but also that of the increasing number of Greater Region commuters driving over the border twice a day (IEA 2019). All consumption considered, 95% of Luxembourg's energy supply is imported.

Acknowledging existing pathways, but choosing another vision

The Plan National Énergie-Climat (PNEC) of Luxembourg states that territorial GHG emissions shall be reduced by 55% by 2030 compared to 2005. The ambitious plan relies on two principal levers in the "decarbonisation toolbox": the deployment of energy generation from renewable sources (electricity and heat), as well as an increase in energy efficiency in most sectors (housing, mobility, industry, services). Energy sufficiency, the third path towards a decarbonised future, is not explored in the PNEC. As a recent OECD report stresses (OECD 2020), the climate targets will not be reached without "redoubled efforts" in terms of environmental legislation, but also, and perhaps more importantly, on a sound economic and social vision. However, while the same report points out the potential of "green growth" as a solution to the climate and environmental emergency, we firmly believe that other visions are more coherent and convincing.

A sector-by-sector approach to decarbonisation

This section gives an overview of the contributions of the mobility, housing, industry, and agriculture sectors to GHG emissions. For three interventions we calculate the impact on GHG emissions as well as other indicators that are part of our set of constraints, including materials use, air pollutants, nitrogen, and phosphorus emissions. These more detailed calculations serve as a proof of concept (POC) of our methodology for calculating the impacts of interventions on GHG emissions and indicators in our constraint set.

The three levers for the energy sector: *sobriété*/efficiency/decarbonisation

Strictly looking at the potential trajectories for a net-zero carbon world proposed by the IPCC, the efforts required by 2050 are staggering. GHG reductions of about 5% per year every year until 2050 will be required globally, while simultaneously increasing the carbon sink potential to ensure neutrality. For energy-using sectors the decarbonisation approach can be decomposed into three main levers, aligned with the framework developed by the French association negaWatt[8]: (1) popularise low-energy sufficient lifestyles (*sobriété* or *Suffizienz*); (2) increase the energy efficiency of the Luxembourg economy; and (3) decarbonise energy production and imports. We take a sector-by-sector approach to understand what each of these levers would mean in their respective, specific context.

Mobility

MODU2.0, the government's viewpoint as a start

As the sector with the highest share of energy-related emissions, mobility must undergo climate change mitigation measures. The MODU2.0 strategy, published in 2018 contains the four main objectives that the Government has set for 2025: (1) incentivise a modal shift in office-commuting, away from car (especially *autosolism*) and towards public transport and soft mobility; (2) increase average occupancy rates of private vehicles from 1.2 to 1.5; (3) enable a modal shift in school commuting, with a higher increase in soft mobility than is planned for objective 1; (4) increase the attractiveness of public transport mostly by reducing delays on existing lines.

We start building our vision on these medium-term, top-down approaches. In concrete figures, according to the EU White paper Roadmap to a Single European Transport Area (EC, 2020) , the transport sector has to contribute to the EU climate engagements by reaching a target of 60% emission reduction by 2050. To reach this target, the following goals have been set (Creos 2018) :

- 50% less 'conventionally-fuelled' cars in urban transport by 2030;
- achieve essentially CO_2-free city logistics in major urban centres by 2030;
- complete phase out of 'conventionally-fuelled' cars in cities by 2050;
- shift of 30% of the road freight to rail or waterborne transport by 2030, 50% by 2050.

[8] A succinct description is available at https://negawatt.org/La-demarche-negaWatt

Peak car?

Shifting away from the car-centric model is a priority. From a utilitarian perspective, automobiles claim space, time, and energy, pollute clean air, produce noise, and hence negatively affect well-being, to deliver a mobility service with a very low efficiency from a collective perspective. While some authors have prematurely claimed that “peak car” had passed in Western Europe, the reality in Luxembourg is different. The number of cars per inhabitants is still increasing, even though it already represents the highest share in the EU, and private vehicles become still heavier and emit more carbon (Gössling 2020). A recent report by the IEA identifies SUVs as the second most important driver of the emissions increase between 2010 and 2018 (IEA 2020). Literature suggests that shifting away from cars can be accomplished by communicating about the positive sides of alternatives, as was done in Copenhagen, whose successful pro-cycling communication never mentioned cars or climate change (Gössling 2013).

Challenging “automobilism”

However, in Luxembourg, automobiles remain a reasonable option for many mobility needs; although they are still today a status symbol for the highest-income segment of society. What will remain of the existing fleet in 2050 will need to be decarbonised, robust, shared, small, and light. Many alternatives exist to decarbonise powertrains, the most energy-efficient of which is the 100% battery-electric automobile. A progressive gasoline and diesel ban is desirable, at least in Luxembourg City and potentially nationally, to achieve these targets, as is planned in London (2030) or Paris (2024 for diesel, 2030 for gasoline). Size must decrease too, not only because vehicles’ size correlates with weight and specific energy use, but also because lightweighting efforts rarely achieve true decarbonisation on the life cycle of a vehicle, as the use of better materials requires supplementary energy in the production phase that may never be offset by use phase savings (Wolfram et al. 2020).

Can the car ever become an “appropriate technology”? [Proof-of-concept]

Downscaling, or purchasing smaller cars, should therefore be encouraged alongside electromobility and car-sharing, which ensures short- to medium-distance mobility (de Blas et al. 2020). Legal limits set on engine power or curb weight can yield substantial results. Paradoxically, the most efficient pathway is a drastic reduction of the stock of cars in the country, while simultaneously increasing the use of each vehicle in terms of passenger-kilometer (pkm). Since vehicles are “materials sinks”, intensifying their use while decreasing their number would automatically decrease environmental impacts and resource requirements per pkm. Aiming at a target of 200,000 cars in Luxembourg in 2050 could achieve a GHG reduction of about 85% for the mobility sector, with electric vehicles accounting for about 80% of this fleet, and the rest divided between plug-in hybrid for exceptional long-distance travel (which could be restricted to rental agencies, for example), or hydrogen fuel-cell and biogas vehicles (fig. 15). This amounts to 260 vehicles per 1000 capita, a level last seen in Luxembourg in 1976 (fig. 16) (STATEC 2020i).

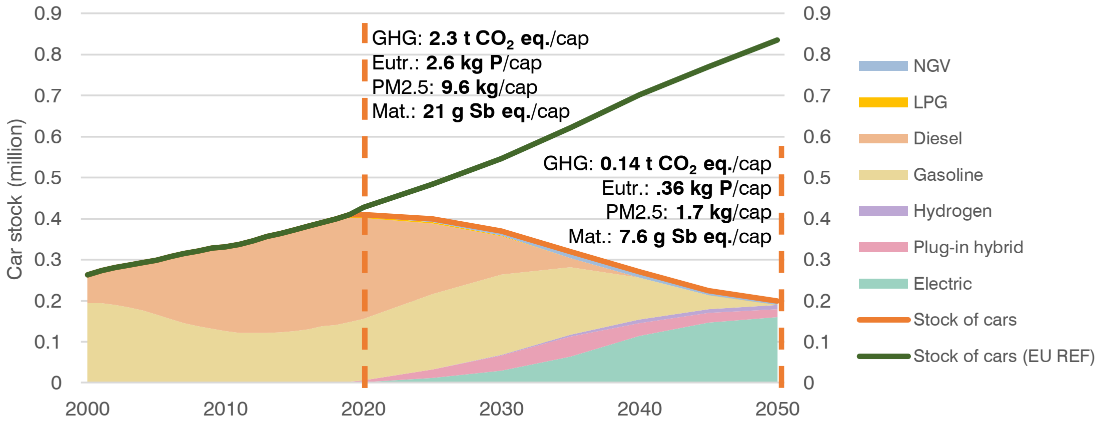


Figure 15. Private vehicle fleet in Luxembourg, illustration of a potential pathway compared with the EU Reference scenario of the PRIMES model. LIST calculations for LiT.

This mobility plan will become possible because of a radically new land use plan devised to enable the 15-minute city, more densely associating the different functions such as housing, working, production, social infrastructure, and leisure. Individual mobility options will only be necessary in the less densely populated rural areas, while travel within cities relies on soft mobility and travel between cities is ensured by public transport.
The resulting carbon footprint of the car fleet in 2050 (4 billion pkm of mobility) could become as low as 140 kt CO_2 eq., or about 140 kg CO_2 eq. per inhabitant, amounting to 9% of the target 1.6 t CO_2 eq./cap carbon footprint (provided that all electricity becomes low-carbon, since it could be double to triple otherwise). Other environmental impacts from mobility would decrease in absolute terms: eutrophication by 88%, particulate matter emissions by 83% and materials by 72%. This example will be further refined in the context of the overall vision.

Figure 16. Luxembourg-City's Grand-Rue in 1976, before it became pedestrian in 1979. Under strict 1.5°C-compliant climate regulations, the number of cars per capita in 2050 should fall to what it was when this picture was taken.

Electromobility

A question that arises is whether a fast deployment of battery-electric vehicles (EVs) is technically feasible, considering the various obstacles encountered today, such as prices, charging station availability, but also global battery production potential. However, EVs' total cost of ownership (TCO) is already falling below that of internal combustion engine (ICE) cars (Desreveaux et al. 2020). This suggests that, given the existing subsidy for the purchase of a new EV, the breakeven point has already been reached in Luxembourg. Half of the fleet in 2040 can therefore have become electric without having encountered any technical or economic obstacles – this roughly corresponds to the number of households that would be living in single-family houses in 2040,[9] for whom charging stations are not absolutely necessary. Plug-in hybrid cars (PHEVs) can fill the gap for such a transition, peaking at 15% of the fleet in 2035 and decreasing thereafter. As the last diesel vehicles are being phased-out, PHEVs keep "shouldering" battery-electric vehicles until 2050. Recent studies have shown that the impacts of PHEVs are highly dependent on users' behaviours, especially regarding charging, since not charging a PHEV ends up being worse for the climate than having a gasoline car (Bannon 2020) – this may be a caveat in case PHEVs become commonplace. For those, and long distance travellers, the P+R (park and ride) system at the periphery of towns must be developed. Notably, equipping such open spaces with quick charging stations is also less complex than in buildings. Although Luxembourgish automobiles are relatively short-lived compared to other EU countries, ownership is still a cause of lock-in; in other terms, buying a diesel car in 2020 means that this car is probably still in use in 2030 if its useful lifetime is not artificially reduced by political decisions. Stock-flow cohort models, which trace production, use, and end-of-life treatment of a vehicle fleet over time, can help to understand this phenomenon and to legislate early to incentivise environmentally-sound decisions by citizens (Fridstrøm et al. 2016).

[9] Assuming the same 63% share as in the latest census of 2011 – STATEC 2013.

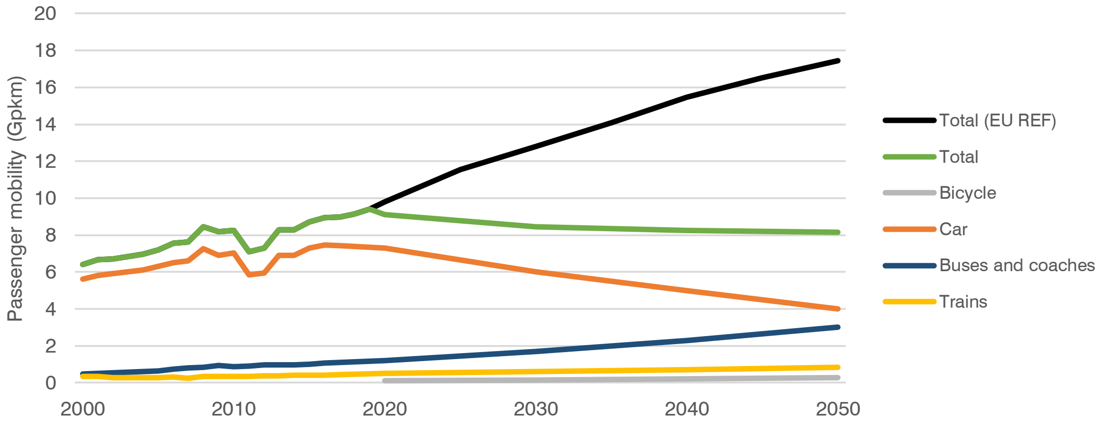


Figure 17. Total road passenger mobility in Luxembourg. Illustration of a potential pathway compared with the EU Reference scenario of the PRIMES model, showing buses, coaches, minibuses and trains breaking even with private cars at 4 billion passenger-kilometers (Gpkm) around 2050.

Soft mobility

Finally, public and soft mobility are the main levers to use in a deep decarbonisation pathway. Free public transport is the first step in making Luxembourg mobility-efficient, as buses, coaches, or minibuses, trains, and trams need to become more attractive to citizens. Similarly, extension of the tramway network between cities as well as stronger connections with the hubs of the Greater Region also need to be developed, as cross-border commuting needs to undergo this modal shift. A milestone in the modal shift could occur just before 2050, when the same number of passengers will have travelled by public transport (by bus, coach, minibus, tram, or train) as by car (fig. 17). The use of bicycles, electric (pedelec) or not, should be encouraged by providing appropriate paths in and between cities. Full isolation from cars by reallocating road space can significantly increase the traffic on cycling paths. Concomitantly with declining air pollution from displacing (cleaner) cars out of inner cities, the physical health benefits of cycling will increase, to add to other advantages, such as mental health and economic savings (Tainio et al. 2016).

Housing

High standards, reduced surface

The Luxembourg residential sector is characterised by a high dwelling surface area, with an average of 86 m^2 for apartments to 186 m^2 for single houses (Zahlen 2014), which inevitably entails high energy consumption in both constructing and heating those units. As advocated by a recent UNEP Resource Panel study (Ali et al. 2020), reducing the floor area per person (from about 53 m^2/capita in 2020 to about 31 m^2/capita in 2050, a value considered average in many European regions)[10] is by definition the only way to increase housing capacity on the same surface area, together with low-rise and multi-family homes (MFH) becoming standard in the Luxembourgish city and rural landscape with a great typological variety. Moreover, it will be necessary to increase the retrofit rate (percentage of retrofitted buildings per year) from the current average of 0.4% (for “medium” renovation interventions, i.e. renovations creating primary energy savings from 30% to 60%) to 3% and improve retrofit standards by decreasing the U-value (thermal transmittance) for external walls to 0.1 W/m^{2}K.

[10] Poland’s per-capita residential floor area is among the lowest in Europe (27 m^2 per capita).

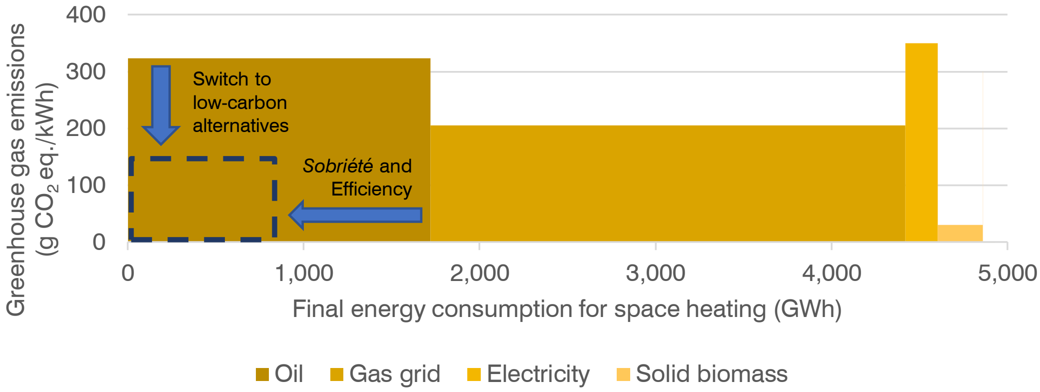


Figure 18. Final energy consumption for residential space heating in Luxembourg, 2017, by GHG emission intensity and total demand.
Areas represent total emissions. Reducing the footprint of heating could be achieved by lowering demand (*sobriété* and efficiency), and shifting away from carbon-intensive energy carriers. LIST calculations for LiT.

Residential heating: a slow but efficient transition

Housing generates about 3 tons of CO_2 eq. per resident per year in 2019 just as a result of its energy use (see fig. 13). Of this amount, 2.2 tons are linked to heating, for a total of 1.2 Mt CO_2 eq. nationally, with roughly half from fuel oil ("mazout") and half from fossil gas heating. The carbon footprint of residential heating alone is therefore higher than the neutrality objective of 1.6 t CO_2 eq. per capita in 2050, which points to the tremendous efforts that need to be made to use less heating. Due to long lifetimes, buildings do not allow as fast a transition as in other sectors (mobility, services, communications). The lock-in effect is therefore high, unless aggressive and sustained retrofitting campaigns take place. However, the long-term impact reduction potential of housing is also significant: combined insulation improvement, reduction of per-capita floor area, as well as changes in heating systems can drastically reduce GHG emissions in Luxembourg's residential buildings (note that we will later refine and extend this preliminary example to the tertiary sector, which also undergoes a radical use shift as remote working becomes the new normal). With Luxembourg holding the European record for highest energy use per dwelling , the room for improvement is immense (ODYSSEE-MURE 2020). At 132 m^2/dwelling for 2.5 persons on average, surface area could be reduced to reach about 90 m^2 in 2050, without losing much comfort. The total surface area could be reduced partly by reclaiming unused office or parking garage space and by focussing on co-housing and cooperatives in order to maximise shared spaces. With 966k inhabitants in 2050 (STATEC 2017) a total of 390k dwellings need to be heated. By 2050, we can conservatively expect that the A+ standards for heating (110 kWh/m2) becomes average, i.e. 3.8 TWh will be dedicated to heating, from 4.9 today (fig. 18). More aggressive renovation and retrofitting measures will be explored in Stage 2 to model how low average specific heating can actually decrease.

Smaller surfaces, better insulation, efficient devices

The residential sector is today mostly heated with fossil fuels, for economic reasons. Of fuel oil and fossil gas, fuel oil needs to be phased out first, because the fuel oil GHG emission factor is higher (fig. 19), but also because fuel oil combustion emits other pollutants, while gas is relatively clean in comparison. Low-carbon heating systems (thermal solar and heat pumps) are costly, so their deployment needs to be accompanied by appropriate governmental subsidies. There is no technical obstacle

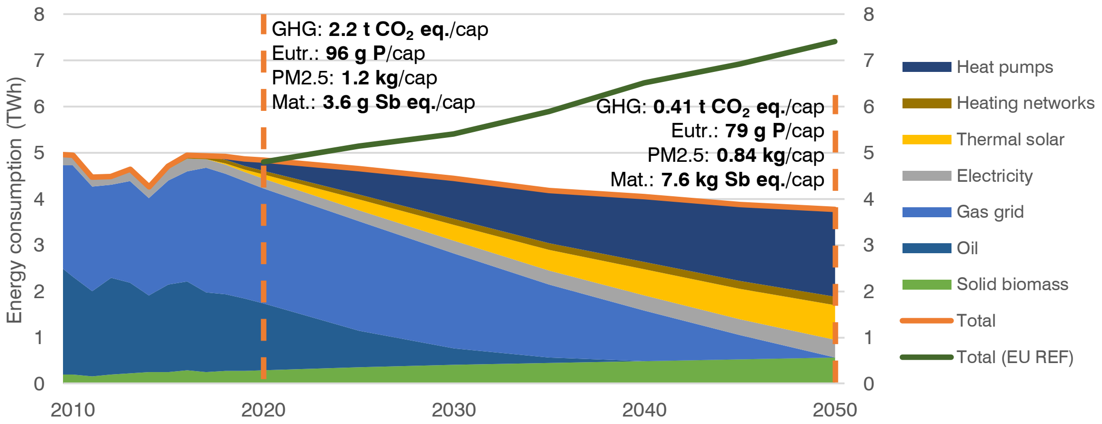


Figure 19. Residential heating energy consumption in Luxembourg, by source, and illustration of a potential pathway compared with the EU Reference scenario of the PRIMES model. LIST calculations for LiT.

to them dominating the market by 2050, such that together with district heating and low-carbon electricity, residential heating can become low-carbon by mid-century. For the share of residential buildings that cannot be retrofitted for heat pumps to be efficient, locally-sourced biomass, used parsimoniously, will serve as a complement. This scenario is an alternative to the PNEC's vision of a biomass-biogas-based heating transition, where heat pumps and solar thermal systems only come as complements. In terms of carbon footprint, life-cycle emissions remain (from manufacturing and energy conversion), but the per-capita impacts of heating can decrease from 2.2 t CO_2 eq. today, to 0.41 t CO_2 eq. in 2050 (about 25% of the 1.6 t CO_2 eq./cap target). Some trade-offs can however be observed on other indicators: either relative, namely for eutrophication and particulate matter emissions (per-kWh impact increases, but slower than demographic growth, and these impacts also become remote instead of local), or absolute for material depletion – due to the higher material requirements of low-carbon heating equipment relative to those of a fuel oil or gas boiler.

Leave fossil fuel heating behind

Pathways to reduce the energy use in buildings' heating systems involve for instance water-to-water heat pumps with a higher coefficient of performance (CoP) than air-to-water or air-to-air ones. More generally, a modular infrastructure of power devices converting electrical energy in thermal (heating or cooling) and back has to be considered. Figure A2 (in the Annex) shows a solution that has been developed within the framework of the research project "Eco-Village Hollerich" and validated on a test setup in the laboratory of Energy Mix at the University of Luxembourg (Uni.lu) (Rafii-Tabrizi 2020). Modularity leads to an easier upscaling or upgrading of the power units individually. This strategy matches with the life cycle of the systems that become obsolete over time. The modules at end-of-life are recycled in accordance with the circular economy concept. In a broader context, the concept of "appropriate technology" – as advocated by E. F. Schumacher (Schumacher 1973), yet only used anecdotally in industrialised countries – is applied here: not only are these energy systems simple enough to be used by anyone, they are also affordable, decentralised, efficient, and environmentally sound.

Industry and Services

The disproportionate, but identity-shaping heavy industry

In 2019, industry was the main user of electricity in Luxembourg. The residential vs. industrial consumption is particularly striking: the residential sector represents 80% of utilities' clients and 14.7% of the consumption; whereas only 0.1% of clients are industries, but consume 58.3% of the electricity – with the rest consisting of commercial clients (ILR 2020). The imbalance is peculiar: even industry-heavy Germany does not show such bias, as 25% of final consumption is residential (36% in France). This observation is an argument for consumption-based carbon- and energy-accounting, as the products of the Luxembourgish industrial sectors (e.g. steel, tyres) are exported, in their vast majority, and the argument could be made that their impacts should logically be allocated to final consumers, not Luxembourg residents. Howbeit, industry, and steelmaking in particular, have always been at the heart of Luxembourg's identity, and there are many levers to support the low-carbon transition of steelmaking, while preserving its competitiveness and desired positive socio-economic impacts. For example, steelmaking consists today mainly of electric arc furnaces (after a transition from blast furnaces in the 1990s, which significantly reduced the country's GHG emissions as a result), which, given the proper sourcing of electricity, could produce low-carbon steel. As it happens, today even blast furnaces (not in activity in Luxembourg anymore) could be decarbonised by using renewably-produced hydrogen instead of coke for the reduction of iron ore.

A future for industries “of the past”?

The industry question could also be addressed from the application side of products made in Luxembourg: will steel products, or tyres made by Goodyear in Colmar-Berg, be used as intensively as today if society manages to shift away from its car-centric approach? The world of 2050 needs to be a “local” world, in which the share of distances covered by car will have drastically fallen. The question arises whether buses, coaches, and the remaining zero-emission vehicles of Luxembourg and Europe will generate enough market demand for car-grade steel and tyres made in Luxembourg considering the current production volume. Solutions exist, and the most promising ones involve changing business models. For example, one way of transitioning would consist in shifting product ownership from consumer to producer. In the case of Goodyear, the company could provide tyres as a service instead of a product. As such, circular economy pathways can potentially increase the intensity and duration of use of a given product and preserve the competitiveness of a potentially declining industry by providing regular revenue streams.

Energy Networks

Increasing the share of renewable power

A share of 50–70 percent of domestic electricity self-generation from renewable energy (RE) sources in Luxembourg is foreseen by the year 2050 (Creos 2020), following a 25 percent share in 2030 according to the PNEC (fig. 20). As illustrated by the “Clever Solar” initiative (Myenergy

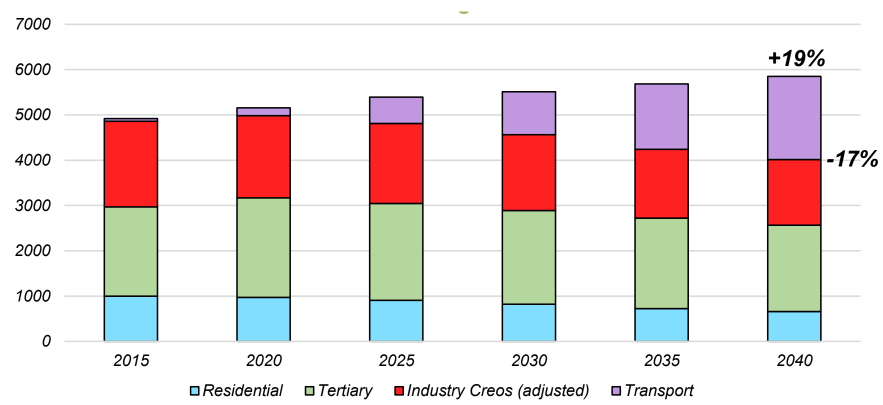


Figure 20. Sectorial evolution of the electricity consumption on Creos grid (GWh). PNEC LU Target scenario.
Electricity consumption in the main consumer sectors.

2020), Luxembourg is accelerating the deployment of small-scale photovoltaics. In 2019, Luxembourg ranked 7th in the EU for installed solar PV capacity per inhabitant at 230 W/capita, but still well behind its neighbour and frontrunner Germany at 590 W/capita (Statista 2020). A range of incentives will be deployed according to the PNEC to increase both small-scale and large-scale renewable energy production. In order to limit the pressure on land and meet our target of not increasing the current level of soil sealing, we propose combined RE production with other land uses, such as the proven technology of rooftop solar but also newer forms of multi-use, such as RE on agricultural land, which is explained further in the section on agricultural measures for decarbonisation and resilience.

Small-scale RE production close to demand sources comes with the benefit of avoiding transmission losses. However, in terms of economy of scale, mid-size power units, for instance from 100 kVA for small residential areas up to 1 MVA for larger ones with some commercial activities, are a good compromise between the centralised larger power plants with losses during energy transportation to the end-user and the less efficient, smaller power plants located close to consumers. Management and maintenance of such installations would be easier as well, since they would remain under the control of the Transmission System Operator (TSO).

The drawback of increasing the penetration of renewables lies in their intermittency. To solve the challenging equation of permanent energy availability with variable renewable energy sources, we need storage, demand-side-management, and load time shift as well as dynamic tariffs (whereby price follows renewable energy generation or low-carbon content of electricity). Such a new dynamic leads to higher flexibility.

Batteries for storage

EVs' joint offer of mobility and energy storage can contribute to curtailing power peaks. With a demand-side power control capability, the EV is able to delay the charging sequence from day to night. No technical obstacle remains regarding the bidirectional use of these storage capacities, but legal terms have to be clarified with the Institut luxembourgeois de régulation (ILR) for certifications and authorisations, as well as ILNAS[11] for the definition of the vehicle-to-grid standard, and its favorable impacts on the prices for the end customer/prosumer.

[11] Institut luxembourgeois de la normalisation, de l'accréditation, de la sécurité et qualité des produits et services.

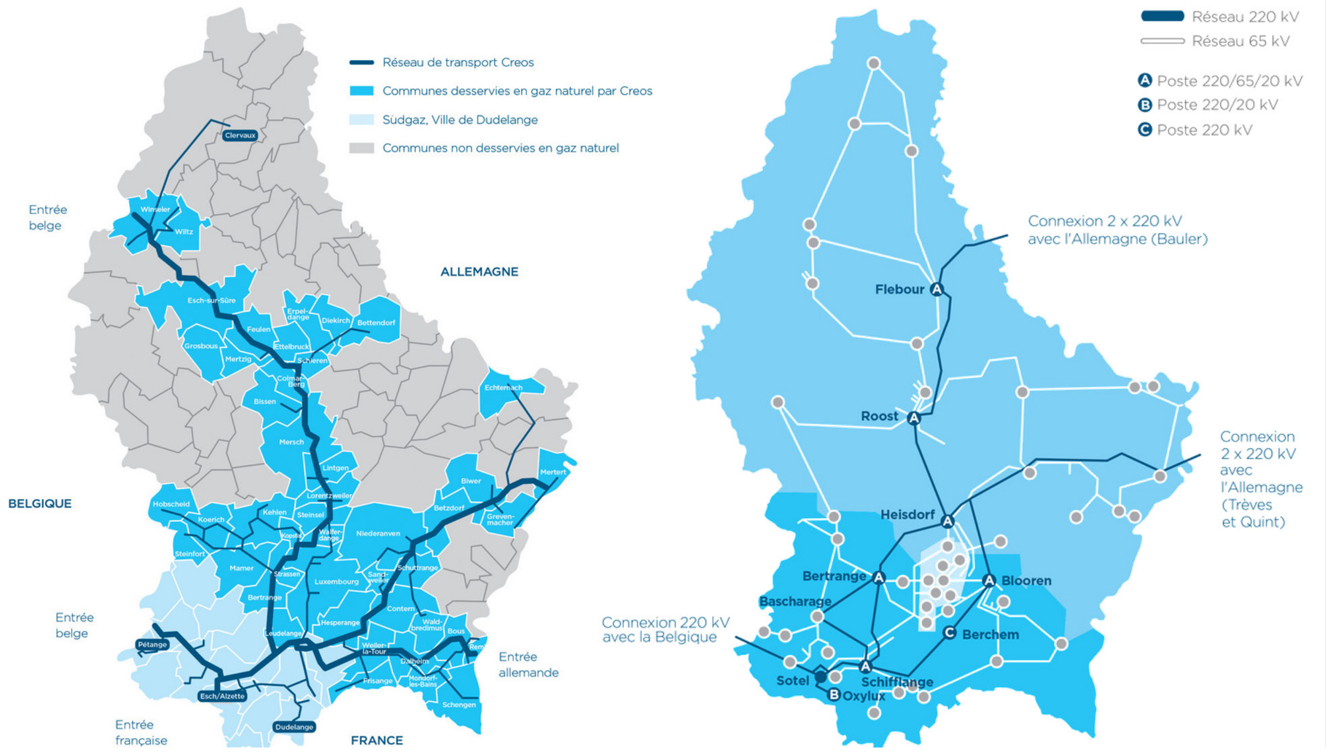


Figure 21. TSOs of electrical (left) and natural gas (right) networks topologies

The role of hydrogen

Power to gas, in particular via hydrogen electrolysis, will play a pivotal role in the medium term for bridging interseasonal energy production and consumption as well as covering peak power demand. A strong collaboration between both the power and the gas TSOs will be key to facilitating combined power-to-gas and gas-to-power energy production (fig. 21).

New energy vector, new investments

The adoption of hydrogen as a new energy vector inevitably requires efforts and investment, but it does not have to start from zero: retrofitted existing gas pipelines can technically transport pure low-carbon hydrogen, as shown across the Greater Region in the Mosel Saar HYdrogen Conversion (mosaHYc) project (ENTSOG 2020). Placed at strategic points on the developing network, trains, buses, cars and trucks would be able to re-fuel hydrogen at dedicated hydrogen stations. It should be noted that hydrogen fuel cell cars are not expected to be deployed widely in Luxembourg, as they offer poor overall energy efficiency (compared to EVs). Hydrogen can also be used as feedstock in the chemical industry, which may be more of interest given Luxembourg's industry fabric.

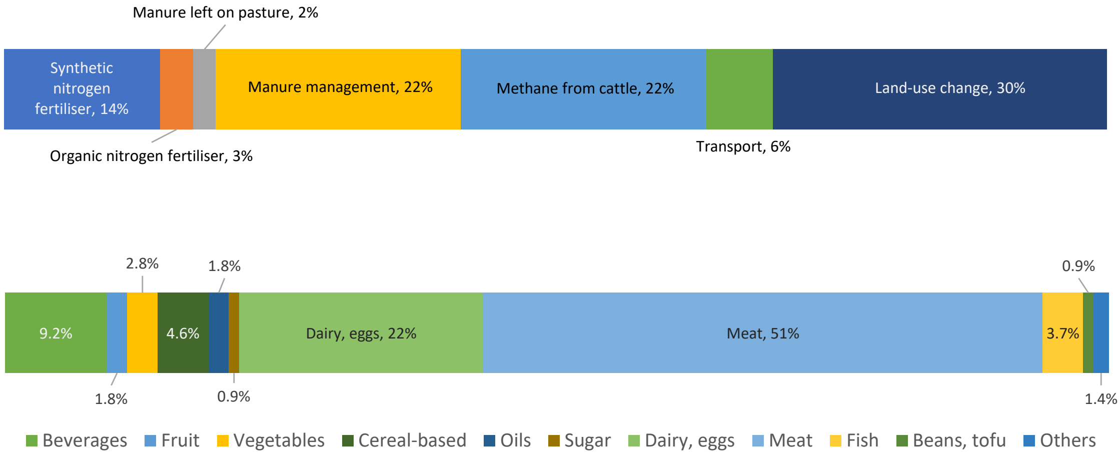


Figure 22. Contribution of supply chain and food categories to GHG footprint of the EU average diet.

Relieving the grid

Moreover, with the help of smart inverters connected to the utility power grid, reversible power-to-gas conversion fuel cell units provide the power supply with a high dependability in terms of flexible use, stability, robustness and fail-safe enabling. Peak power demand of future potential large-scale data centres may be absorbed by hydrogen fuel cells and battery-fed uninterruptible power supplies.

Agriculture – A source of biogenic GHG emissions

In contrast to most other sectors, agriculture is a direct source of GHG emissions, including nitrous oxide and methane from manure management, enteric fermentation, and soil management. Soil management emissions in crop production depend on fertiliser applications and tillage practices. Part of these emissions can be attributed to the livestock sector due to the production of livestock feed. Manure management and enteric fermentation emissions are specific to livestock production. While historically livestock transformed inedible materials into protein-rich food, today livestock production has intensified and relies on feed production from arable cropland (Leip et al. 2015). As such, the livestock sector accounts for almost three-quarters of food-related emissions in the EU (Sala and Castellani 2019). In Luxembourg, direct, biogenic emissions from agriculture amounted to 675 kt CO_2eq/year in 2015 or 5.2% of total GHG emissions in Luxembourg, with manure management and enteric fermentation accounting for close to 80% of these emissions (Eurostat 2017).

Direct, biogenic agricultural emissions can only be addressed by changing agricultural production systems, such as reducing methane generated by ruminant livestock through feed additives, reducing tillage, avoiding overapplication of fertiliser, or by changing diets to shift away from livestock with larger GHG emissions per gram of protein. Fossil fuels also play a role in food production, from direct consumption by agricultural machinery or in the production of synthetic fertilisers, pesticides and packaging, food processing, and distribution. Decarbonisation in electricity production and in transportation will also reduce supply chain emissions in food production.

Transport accounts for only 6% of food-related GHG emissions, so eating local food provides smaller climate benefits than commonly believed (fig. 22). The main decarbonisation interventions in agro-ecology include reducing meat consumption, as a particularly GHG-intensive food item. In addition, reducing food waste in households, food service and along the supply chain, is a promising intervention, since food waste accounts for 25% of food-related GHG emissions in Luxembourg (European Parliament 2017). Expanding the carbon uptake of land through intensification and extensification of forest land, and implementing agricultural production practices that reduce methane and nitrous oxide emissions from soils and livestock are other ways of mitigating climate change.

Reducing meat and dairy consumption: Switching to grass-fed, organic production
[Proof of concept]

On a global scale, about one third of arable land is used to produce feed for livestock. In Luxembourg, the share of arable land used for feed production is closer to 75 % (Ministère de l'Agriculture, 2020). Consequently, this brings about large trade-offs between producing food directly for human consumption and producing food for human consumption via animals, as the latter entails large conversion losses (Schader et al. 2015). This conversion loss in combination with the climate impact of the livestock sector (83% of EU food-related GHG emissions) means that it is important to combine strategies for sufficiency (e.g. reduced demand for animal products) and consistency (e.g. reduction of food-competing feed components in livestock rations, also known as "feed no food") when envisioning a food system for Luxembourg in 2050 (Sandström et al. 2018). The latter will automatically also reduce the availability of livestock products and, as Schader (Schader et al. 2015) put it, "shift the focus from livestock's role in the food system as a source of high-quality protein, to another role, which is to use resources that cannot otherwise be used for food production". One such resource is permanent grassland, which makes up ca. 50% of Luxembourg's agricultural area (Ministère de l'Agriculture 2020) .

Based on the current area of permanent grassland, an assumption of 30% clover-grass lays in the arable crop rotation to ensure soil fertility, 100% organic production and the use of a dual-purpose breed, such as European Simmental cattle, our partner IBLA, calculated that the raising of 64,000 cattle could be supported in Luxembourg (compared to 194,000 cattle in 2019 (Ministère de l'Agriculture 2020), producing 6,600 t meat/ year and 78,000 t dairy/year. Converted to retail food weight, this would equal 4.8 kg beef meat/person and year and 81 kg dairy/person and year at a population of 966,000 inhabitants in 2050. Comparing this to the 20 kg of beef meat (retail weight) consumed/person in Luxembourg in 2019, this would equal a 76 % reduction. Reducing beef consumption to 4.8 kg beef per person per year amounts to a weekly consumption of 90 g, which together with the more than 500 g of pork and 500 g of poultry consumed per capita, is still above the 300-600 g weekly maximum of meat consumption recommended in the German Nutrition Society (DGE 2020). The 64,000 cattle could supply Luxembourgers with just under 2 L milk per day, which is also sufficient to meet the daily consumption of 200-250 g (about 206-260 mL) low-fat milk and 50-60 g low-fat

	2019	2050 (grass-fed, organic)	Change (%)
Total number of cattle	194000	64200	-67%
Permanent grasslands (ha)	67900	67900	
Arable land (ha)	62000	62000	
Arable land used for human food (ha)	15700	43400	176%
grain legumes	0	7100	
cereals	13500	23700	
vegetables (incl. field vegetable such as potatoes)	958	9600	
oleaginous crops (e.g. sunflowers, rapeseed, etc)	0	1690	
vineyards	1290	1290	
Arable land used for feed (ha)	46000	18600	-60%
maize	15100	0	
cereals total without wheat and spelt	13900	0	
grain legumes	407	0	
rapeseed	3930	0	
beets	79	0	
field fodder	12600	18600	48%
Share of arable land used for feed production (%)	74.3	30	
Import of soybean (t)	25900	0	
Total fungicides and herbicides (kg active ingredients, 2018) on arable land used for feed production	90500	0	
N mineral fertiliser (t) on agricultural land used for feed production	11900	0	
P2O5 fertilisers (t)	849	0	
Beef production (t carcass weight)	16300	6590	
Beef consumption (retail kg/inhabitant)	19.5	4.62	-76%
Dairy production (t)	421000	78100	
Dairy consumption (L/inhabitant)	694	80.6	-88%
Embodied GHG emissions			
soybean import (t CO_2 eq.)	23100	0	
pesticide use on land for feed production (t CO_2 eq.)	2260	0	
fertiliser use on land used for feed production (t CO_2 eq.)	13300	0	
Direct GHG emissions from livestock (t CO_2 eq.)	952000	256000	
Total GHG emissions from livestock and feed production (t CO_2 eq.)	990000	256000	-74%
Nitrogen emissions to water from land for feed production (t)	2390	0	
Phosphorus emissions to water from land for feed production (t)	56	0	

Table 3. Agricultural land use, beef and dairy production, emissions, by scenario

Note: Calculations by authors using agriculture data from the Luxembourg Statistics Portal, assuming 20% loss of N to water,15% loss of P to water, embodied GHG emissions of 0.89 t CO_2eq / t imported soybean, 370 MJ/kg ai energy use in pesticide production and 0.06759 kg CO_2eq/MJ emission factor, embodied GHG emissions of 1.112 kg CO_2eq/kg N fertilizer, livestock GHG emissions of 22.2 kg CO_2eq/kg meat and 1.4 kg CO_2eq/kg dairy.

cheese recommended by the German Nutrition Society. Thus, switching the cattle production system in Luxembourg to entirely grass-fed, organic production would reduce the number of cattle that Luxembourg could support with its existing grassland but still provide enough dairy and beef for Luxembourgers to meet the German dietary guidelines.

The switch to grass-fed, organic beef and dairy production reduces GHG emissions by 1.32 t CO_2eq capita^{-1} year^{-1} and comes with the co-benefits of reducing nitrogen and phosphorus emissions as well by 3.8 kg N capita^{-1} year^{-1} and 89 g P capita^{-1} year^{-1} (Table 3). The freed-up arable land that was previously used for feed production can in this scenario be used to produce grain legumes, cereals, vegetables, and oleaginous crops for human consumption. One of the benefits of switching to grass-fed production is that Luxembourg no longer needs to import 26,000 tons of soybean feed as well as 850 tons of mineral P fertiliser used in feed production. The remaining cattle produce enough manure to meet the P needs of the grassland as well as the food and field fodder production on arable land. Eliminating the need to import mineral phosphate is welcome given global shortages in phosphate rock (Alewell et al. 2020).

Extending this strategy of “feed no food” to non-ruminant meat production would liberate at least 50 % of the arable land for food production for direct human consumption or other uses (Ministère de l'Agriculture 2020). Non-ruminant meat (pork and poultry) production would decrease by 77%, while egg production would decline by 90% (Schader et al. 2015). This calculation should also be extended to other livestock categories to consistently use arable land primarily for food production directly for human consumption.

Amplifiers – participatory approaches, integrative development, transition governance, capacity building

The proposed GHG emission reduction pathway can only be realised at the required scope and speed when stakeholder groups across sectors and domains and increasing parts of the population actively participate and amplify this transition. As changes in infrastructure and changes in behaviour need to go hand in hand, more than simple acceptance is needed: just as many citizens and local communities need to become engaged in co-shaping and co-driving the transition.

Participatory and community-led approaches have unique potential to contribute to reaching ambitious climate targets (Penha-Lopes & Henfrey 2019). A meta-study has shown that residents of ecovillages, for instance, emit 35% less GHG than the respective national average, with the most successful example reaching a 70% reduction (Daly 2017). This shows how far the integrated regenerative design principles that guide the development of ecovillages can carry local solutions even if the wider context operates in ways that are yet at odds with those principles. In ecovillages the transition domains of our decarbonisation and resilience strategy are highly interconnected: green building and retrofit technologies, co-working and co-housing with a healthy mix of personal and community spaces, local food and energy production and consumption based entirely on agroecology and renewables, including practices of carbon capture in soils, as well shared mobility, participatory self-governance, co-design, while also caring for biodiversity, the water cycle, social inclusion and vitalisation of the local economy. All this together leads to low-impact lifestyles and connected built/unbuilt environments. Some ecovillages pursue the ambition to become carbon-negative.

More information on the amplifying effect of participatory approaches on decarbonisation efforts is presented in the annex.

Proposed interventions – A decarbonisation path and timeline to reach 1.6 ton CO_2 eq./capita

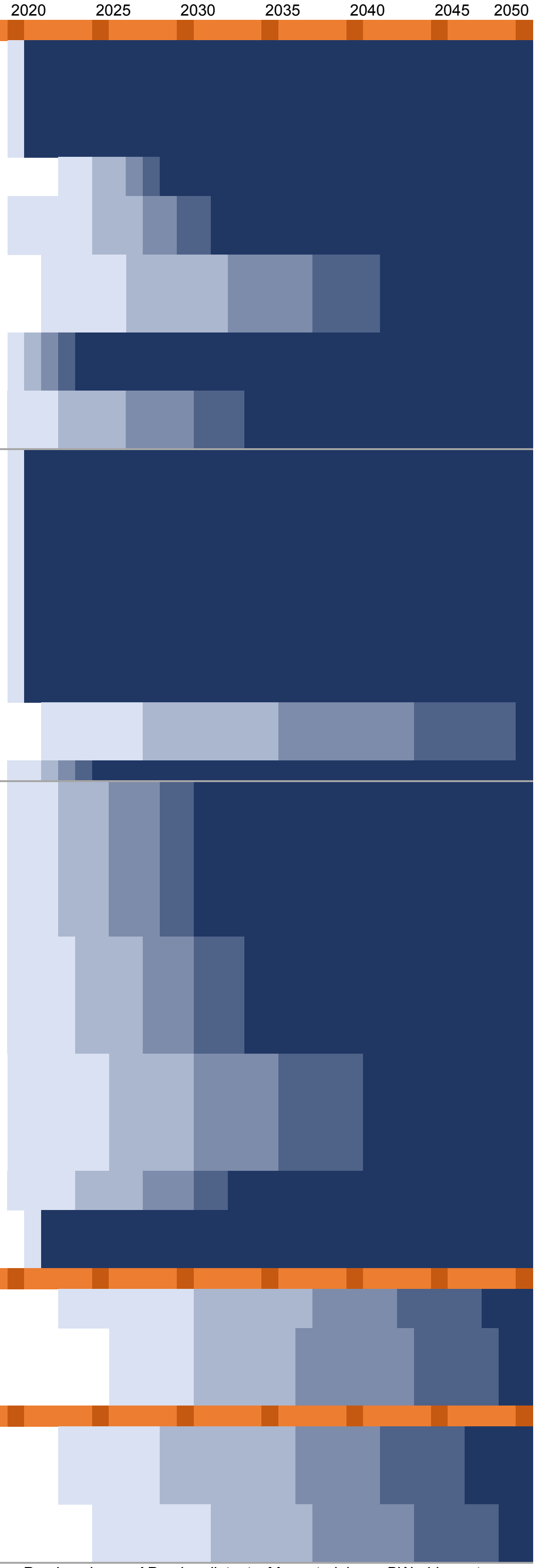
In the previous section we presented the main sectors and activities that contribute to Luxembourg's GHG footprint. We also presented in greater detail the impact of three interventions in mobility, housing, and food/agriculture on GHG emissions as well as materials, air pollutants, nitrogen, and phosphorus emissions. In this section we combine these three interventions with others to present one possible decarbonisation path for Luxembourg.

In Table 4, we summarise several specific interventions with the main goal of decarbonisation. For each intervention we list the impact on our set of indicators, and highlight in bold those indicators, for which we quantify the impact. We also describe the spatial implications of the interventions, as well as the impact on the Greater Region. Finally, we approximate how quickly an intervention can be taken up or implemented. Here we differentiate between infrastructure investments, with long planning and build lead times, and regulations, which can in theory be implemented quickly, as it is mainly political will rather than technical or physical constraints that determines the speed of implementation.

The intervention table is a decarbonisation toolbox, in which all tools have to be used if the target of sustainable GHG emissions is to be reached. Based on selected interventions from this table and in particular the three mobility, housing, and food/agriculture interventions that serve as a proof of concept for our impact assessment methodology, we have constructed a decarbonisation path for Luxembourg. In particular, we include the following additional interventions: a 90% reduction in passenger aviation, elimination of fuel tourism by aligning fuel taxes with those of our neighbouring countries, an 80% reduction of food waste from 25% to 5%, an 88% reduction in the consumption of goods, a 90% reduction in GHG emissions in the public sector, and decarbonisation of the electricity grid in 2050 as pledged by our neighbouring countries. Further details on these measures are provided in Table 5.

Together, these measures reduce GHG emissions resulting from consumption in Luxembourg (by residents and non-residents) from 13.7 Mt CO_2eq. in 2020 to 1.6 Mt CO_2eq. in 2050 (fig. 23). In Stage 2 of the proposal, a more detailed decarbonisation path will be generated, by calculating the impact of the remaining interventions in the decarbonisation table and adjusting the "amount" of the selected interventions to meet the target. While our objective function relates to reducing consumption-based GHG emissions per capita for Luxembourg residents, we nevertheless present the decarbonisation path for total consumption-based emissions for residents and non-residents combined to draw attention to the outsize role that fuel tourism plays in GHG emissions. Eliminating fuel tourism would reduce consumption-based GHG emissions in Luxembourg by 5.4 Mt CO_2eq. or 40% of total emissions in 2020. Figure A3 in the Annex presents the decarbonisation path for consumption by residents only, which excludes the contribution of fuel tourism to the 2020 total (and thus also as a measure for reduction).

Goal	Proposed Intervention	Impact	Spatial implications and impact on GR	Type
Mobility				
Switch away from fossil fuel mobility	Extend subsidies for electric car purchase to second-hand vehicles	**GHG, AP, M**		R
	Align fuel taxes on neighbouring countries' levels	**GHG**	Reduced lorry and passenger vehicle travel through country	R
	Develop fast charging stations	**GHG, AP**	Extend fast charging stations across GR	I
	Electrify the passenger vehicle fleet, install charging stations in residences	**GHG, AP, M, BW**		B, R
	All public transport should be fossil free (with exceptions for long-distance buses)	**GHG, AP**	Electric or hydrogen-powered public transportation infrastructure across GR	I
	Gamification to encourage soft mobility (MUV, Survcoin, mam Velo op d'Schaff)	**GHG, AP**	Coordinate soft mobility infrastructure across GR	T
	Extend bike network, such that any destination can be reached safely by bike	**GHG, AP**	Extended bike network, linked to GR	I
Switch away from car-centric mobility	Align fuel taxes on neighbouring countries' levels	**GHG, AP**	Reduce size of petrol stations along border, reduced lorry and passenger vehicle travel through country	R
	Abolish commuter subsidy (currently 214.50€ per month)	**GHG**	Creates an incentive for telework or living closer to the workplace	R
	Regulate the fiscal status of company cars	**GHG**		R
	Develop a progressive tax on weight or power for private vehicles	**GHG**		R
	Extend rail network, reduce highway network	**GHG, M, SS**	Extended rail network, reduced highway network, in coordination with GR	I
	All inner city streets pedestrian	LS	Car-free innner city streets	R, I
Reduce energy use in transportation	Incentives for car-sharing, such as HOV (high-occupancy vehicles) lanes	**GHG, M, LS**	Occupancy rates, coordination of car-sharing across GR	R, I
	Reduce commuting through increased telework and local co-working spaces	**GHG, AP, LS**	Reduced commuter movements Decrease of office surface Adapted building stock / multifunctional spaces	R, I
	Increase free spaces and leisure activities next to settlements Increase the porosity: the area of urban parks, urban farming, urban parks	**GHG**, AP, **LS**	Less commuter movements for leisure. Hybrid land use patterns. Increased attraction of regional geography for leisure	R, I
	Transform shopping centers and commercial areas. Regionalisation of production. Integration of retail in neighbourhoods	**GHG**, AP, LS	Less commuter movements for commerce. Smaller urban structures, more hybrid land use, urbanistic and architectural typologies	R, I
	Reduce leisure travel to one flight every two years	**GHG, LS**	Reduced air travel	B, R
	Ban (or highly tax) flights with a <5h train alternative	**GHG, LS**	Reduced air travel, increased train travel, extended rail network	R
Power Sector				
Reduce GHGE in power sector	Invest in renewable electricity, 25% by 2030 (PNEC)	**GHG, AP, M**	Incresaed RE installations in rural and urban areas	R, I
	Favour interconnections from neighbouring low-carbon grids, increasing interconnections to at least 900 MW with each neighbor	**GHG**	Fortified or additional cross-border transmission lines	I
Consumer Goods				
Reduce GHGE embodied in consumer products	Extend life-span of products through design (longevity, repairabilty) and Product-Service-Systems (PSS)	**GHG, AP, M,** LS	Infrastructure/facilities provided decentrally (e.g. at residential neighbourhood level)	R, B
	Re-regionalise value chains in manufacturing	**GHG, AP**, M	Changing land-use patterns Adapted production sites Decentralised logistics	R



Note: Indicators that we quantify are in bold. GR - Greater Region, GHGE - GHG emissions, N - nitrogen, P - phosphorus, AP - air pollutants, M - material use, BW - bluewater use, CU - carbon uptake, B - biodiversity, SS - soil sealing, LS - life satisfaction, R - regulation, I - infrastructure, B - behavioural change, T - technology, A - agricultural practice. Darker blue represents increased uptake or implementation of intervention.

Table 4. Proposed interventions with a focus on decarbonisation

Goal	Proposed Intervention	Impact	Spatial implications and impact on GR	Type
Buildings and Cities				
Reduce GHGE related to building sector	Conceive modular buildings according to Circular Economy principles	**GHG**, **AP**, **M**	New building typologies Regional labour markets	R, I
	Decrease steel and concrete in construction, increase of timber structures, decrease the amount of materials	**GHG, M, BW**		R, I
	Regional sourcing of building materials	**GHG**, AP, **M**, LS	Regional sourcing of construction materials / components	R, I
	Reduce net floor area per capita, Prefer multifamily houses to single (detached) houses	**GHG**, **M**	New typologies which are both: more dense and more porous. Integration of shared spaces	R, I
	Fuel switching for heating purposes (from oil, gas, to biomass, heat pumps, district heating)	**GHG**, **AP**, **BW**		R, I
Reduce energy use in buildings	Push for a stringent building code, with high standards for insulation and energy efficiency	**GHG**, **M**		R
	Renovate buildings with low-quality insulation	**GHG**, **M**	Visible construction only during renovation period	R, I
	Educate citizens on their energy use (deploying smart metering)	**GHG**, LS		O, I
	Install green roofs to regulate indoor air temperature and save energy, purify air, increase biodiversity, provide rainwater buffer	**GHG**, AP, B, **LS**	Visibly greener cities	R, I
Reduce GHGE in cities	Increase cold air corridors by decreasing sealed land, increasing parks and urban albedo	**GHG**, LS	Visibly greener cities	R, I
Food and Agro-Ecology				
Reduce consumption of GHG-intensive foods	Reduce meat consumption	**GHG**, **P**, **N**, **BW**, **LS**	Changing land-use patterns Change in logistics Reduction in meat exports and imports Adapted production sites Decrease in storage spaces	B, R
	Reduce the consumption of exotic and out of season fruit and vegetables	**GHG**, **P**, **N**, **BW**, LS	Change in logistics	B, R
	Introduce CO2 tax (border adjustment) & exclude high-GHG goods from liberalisation	**GHG**	Change in logistics	R, I
	Create transparent and easy-to-read food labels and associated app in regards to the sustainability of products	**GHG**, P, N, BW		R
Reduce food waste	Weighing of leftovers in food service to better adapt portions	**GHG**, P, N, BW		R
	Tax food loss and waste in supply chain and in households	**GHG**, P, N, BW		R, B
	Promote food donations of leftovers to social and solidarity sector	**GHG**, P, N, BW, LS		R, B
	Develop and run sensibilisation campaigns on food waste reduction	**GHG**, P, N, BW		O
	Feed-no-food in animal husbandry: only use by-products from other food production processes (e.g. draff) as animal concentrate feed sources in order to free up arable land for food production	**GHG**, P, **N**, CU, BW, **B**	Change in logistics Adapted porduction sites	R, A
	Forbid subsidised exports of lower quality / less wanted food products (i.e. chicken parts that are not legs or breasts) and ensure nose-to-tail usage of all slaughtered animals	**GHG**, P, N, BW	Change in logistics	R, B
Reduce soil-management GHGE	Use of reduced tillage practices (incl. no-till in vegetable production) as much as possible (first reverse glyphosate ban)	**GHG**, **CU**, P, **N**, **B**, **BW**	Changing land-use patterns	R, A
	Use of rotational grazing schemes to maximise soil carbon retention	**GHG**, CU, **N**, **B**	Changing land-use patterns	R, A

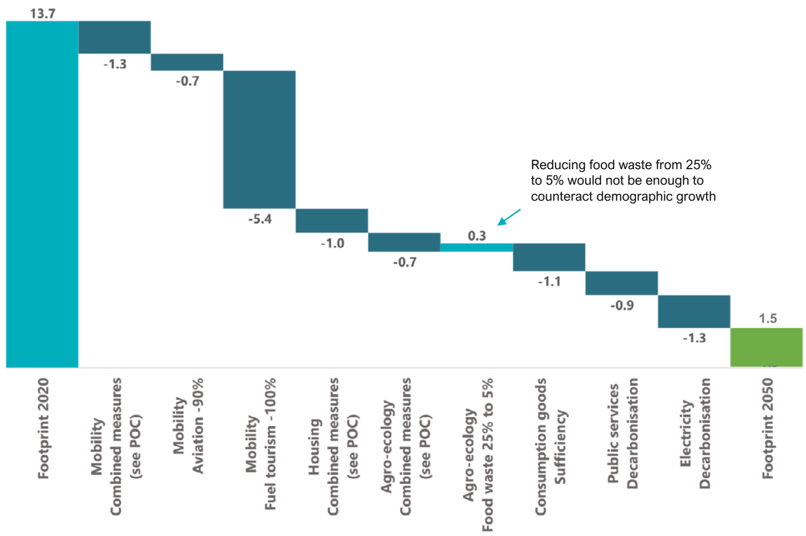
Note: Indicators that we quantify are in bold. GR - Greater Region, GHGE - GHG emissions, N - nitrogen, P - phosphorus, AP - air pollutants, M - material use, BW - bluewater use, CU - carbon uptake, B - biodiversity, SS - soil sealing, LS - life satisfaction, R - regulation, I - infrastructure, B - behavioural change, T - technology, A - agricultural practice. Darker blue represents increased uptake or implementation of intervention.

Goal	Proposed Intervention	Impact	Spatial implications and impact on GR	Type	2020	2025	2030	2035	2040	2045	2050
Food and Agro-Ecology (cont'd)											
Reduce GHGE in food production	Eliminate fossil fuels in food production (e.g. electric- or hydrogen-powered tractors and trucks)	**GHG**, M, **AP**		R, A							
	Fund research on HFC leakage reduction during food transportation and storage	**GHG**, AP		R							
	Eliminate the use of synthetic mineral N fertilisers	**GHG**, **N**, AP, **B**		R, A							
	Fund research on sustainable food production practices/systems, incl. GHG reduction methods and technologies	GHG, CU, P, N, BW, B		R							
	Prohibit the use of peat as a growth substrate	**CU**, **B**	Changing land-use patterns	R, A							
	Reduce application rate of N from (organic) fertilisers (mineral fertiliser use is already prohibited through another intervention)	CU, GHG, N, P, **B**	Changing land-use patterns	R, A							
	Increase the use of slurry application methods that are close to the ground	GHG, N	Changing land-use patterns	R, A							
	Implement organic management systems on 100% of agricultural land, and further improve this system based on ideas from agro-ecology	**GHG**, **CU**, P, **N**, **B**	Changing land-use patterns,	R, A							
Reduce livestock GHGE	Improve organic fertiliser management to reduce storage under anaerobic conditions	**GHG**, P, N, B	Changing land-use patterns	R, A							
	Promote small-scale biogas plants to capture methane emissions during organic fertiliser storage and digestion of other biomass wastes	**GHG**, **N**		R, A							
Optimise land use	Incentivise multi-use for combined RE and agriculture (agrivoltaics)	**GHG, SS, BW**	Changing land-use patterns Multi-functional land-use	R, A							

Note: Indicators that we quantify are in bold. GR - Greater Region, GHGE - GHG emissions, N - nitrogen, P - phosphorus, AP - air pollutants, M - material use, BW - bluewater use, CU - carbon uptake, B - biodiversity, SS - soil sealing, LS - life satisfaction, R - regulation, I - infrastructure, B - behavioural change, T - technology, A - agricultural practice. Darker blue represents increased uptake or implementation of intervention.

Sector	Measure	Detail
Mobility	Combined measures (see POC)	- halve national car fleet, per-capita car/3 - 80% electromobility + biogas, fuel cell - sharing (from 1.2 to 1.6 passenger/vehicle)
Mobility	Aviation -90%	- flights with a <5 hour train alternative banned - sufficiency: one flight every two-year
Mobility	Fuel tourism -100%	- alignment of fuel taxes with neighbouring countries
Housing	Combined measures (see POC)	- smaller surfaces: from 53 to 31 m2/person - fuel oil and gas phase-out - efficient housing: from 163 to 110 kWh/m2
Agro-ecology	Combined measures (see POC)	- reducing beef and dairy consumption by switching to grass-fed, organic production - public campaigns for "quality instead of quantity" to reduce weekly consumption of meat and dairy
Agro-ecology	Food waste 25% to 5%	- reduction of food waste from 25% to 5%
Consumption goods	Sufficiency -88%	- extend new product (home appliances, IT) lifetimes × 2 - large-scale second-hand market (product second life) - sharing economy (double service/product)
Public services	Decarbonisation -90%	- overall decarbonisation of services (electrification whenever possible, sufficiency)
Electricity	Decarbonisation	- neighbouring countries decarbonising lead to a cleaner grid in 2050 - excludes increase in electromobility, heat pumps, and other measures addressed elsewhere - includes commercial consumption (offices, malls…) and home appliances
All	Rest of measures	- decarbonisation of freight - large-scale vegetarianism - decarbonisation of agricultural processes

Table 5. Description of interventions calculated for the decarbonisation path



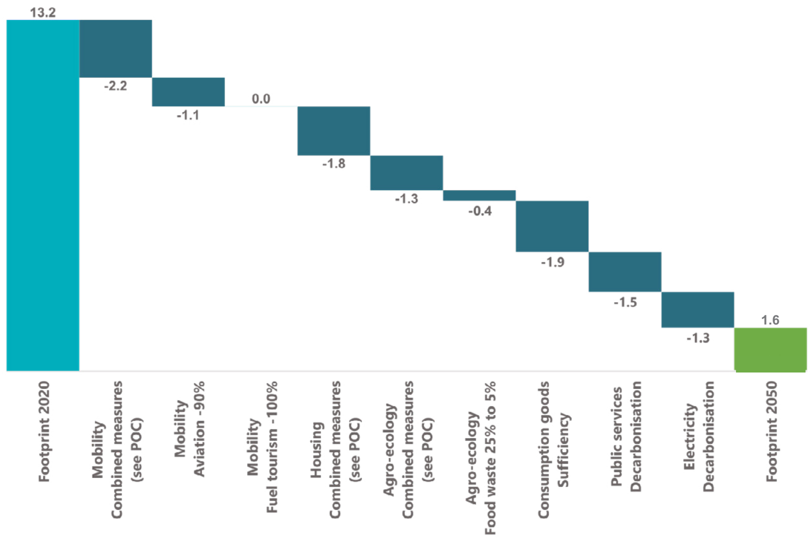


Figure 23. Overall impact of decarbonisation measures 2020-2050 (all consumption, Mt CO_2 eq.).
Impact of decarbonisation measures, including the three proofs-of-concept (mobility, housing, agro-ecology, which are sets of combined measures), scope: all consumption (by residents and non-residents) in Luxembourg.

Figure 24. Overall impact of decarbonisation measures 2020-2050 (t CO2 eq./cap).
Impact of decarbonisation measures, including the three proofs-of-concept (mobility, housing, agro-ecology, which are sets of combined measures), scope: per-capita footprint of Luxembourg residents.

Our decarbonisation path for consumption-based emissions in absolute rather than per-capita terms takes into the expected population growth as detailed in Table 2. As the Luxembourg resident population is expected to increase by about 54% (from 626,000 in 2020 to 966,000 inhabitants in 2050), all climate change mitigation measures should offer at least a 35%* per-capita decrease in emissions in order not to be offset by demographic growth. Reducing food waste from 25% to 5% of total food production, for example, does not provide a sufficient emission reduction to overcome the expected population growth from 2020 to 2050.

Figure 24 shows the decarbonisation path on a per-capita basis for Luxembourg residents. Our selected measures reduce consumption-based GHG emissions per capita from 13.2 to the target of 1.6 t CO_2eq. per capita target associated with the 2°C Paris climate warming scenario. A description of how the implementation of these interventions would change current lifestyles is provided below.

*Equal to the population ratio: 626000/966000 - 1 = -35%

Mobility contributes the lion's share of greenhouse gas emissions in Luxembourg, so focusing on decarbonising this sector brings the most benefits. Reducing the use of cars (to 4 billion pkm in 2050, or ~4100 km per year per resident on average) is the main lever, together with downscaling car segments, car-sharing, and increasing the share of electrified powertrains. If such changes can technically be enforced legally, they will more likely need to come from changing mindsets and overcoming car culture. Company cars will need to lose their fiscal advantages, as well as the "fuel cards" of their users. Commuting subsidies could also be challenged: for the sake of climate, should we not rather subsidise inner city rents than commuting costs (Steinsland et al. 2018)?[12] Work patterns are changing: home office is increasingly accepted, and commuting distances will become shorter in the 15-minute city paradigm, which will alleviate the pressure on technological and behavioural levers. More than 2 t CO_2eq. per capita could be saved.

Additionally, air travel, which is the most emissions-intensive mode of travel, needs to be reduced both for business and private purposes – an objective that also requires a deep culture shift. Traveling in 2050 will take a different dimension: most tourism will need to be more local (by public transport), or to be envisaged at longer timescales, e.g. with the use of night trains. International aviation (*de facto* all commercial aviation in Luxembourg) is technically outside accounting frameworks, we do not have precise consumption numbers; however, we estimate that a reduction in leisure flights from 6 to 1 flight per year[13] could yield more than 1 t CO_2eq. per capita of savings.[14] Finally, getting rid of fuel tourism by 2050 could achieve the highest share of emissions cuts, but this would not reduce the resident-only carbon footprint (only that of all consumption). Considering the revenue from fuel excises, aligning fuel prices with those of the Greater Region will most likely be a difficult economic decision, but a necessary one if safe climate targets are to be respected.

Housing, especially heating, is the next major source of GHG emission savings. A combination of reduced living area, retrofit of dwellings, and a phase-out of fossil energy carriers will bring considerable savings, despite demographic growth. While energy demand would slowly decrease (from 4.8 to 3.8 TWh) because of efficiency measures, heat pumps and solar thermal devices, as well as biomass systems to a lesser extent, could progressively replace their fossil counterparts to minimise GHG emissions. Efficient buildings have (much) better insulation than is average in the existing stock, via the use of low-heat transmittance materials, but they also make good use of their location (e.g. with sun-oriented windows); green roofs are also an effective insulation option. Heating represents the majority of housing emissions, but other measures exist. Decarbonising the construction sector is a difficult task, notably cement manufacturing is a direct emitter of CO_2 via the limestone calcination process and electric-powered construction machines are not commercially available, but efforts are made towards optimising resources (e.g. the SUCCESS project suggests that construction logistics could be greatly improved – LIST 2020). The use of electrical appliances, which become more and more efficient, should also be encouraged (yet this is a second-order issue if the electric grid becomes cleaner).

Food consumption contributes 2.5 t CO_2eq. $capita^{-1}$ $year^{-1}$ or close to

[12] Abolishing commuter tax credits is efficient in reducing GHG emissions, but increases low- vs. high-income inequalities substantially (Steinsland et al. 2018).

[13] 1 flight per year per person means that a round-trip could be planned every second year.

[14] This number is a conservative estimate as there is no exact method to determine the global share of flights due to Luxembourgers.

20% of the average Luxembourgish resident's consumption-based GHG footprint. Meat consumption accounts for 50% of diet-related GHG emissions, so reducing meat consumption is a high-impact measure for our decarbonisation path. It comes with multiple co-benefits. First, high meat consumption is associated with obesity (You & Henneberg 2016). Second, feed production for livestock contributes to nitrogen and phosphorus emissions to waterways and marine and freshwater eutrophication.
We calculated a very specific type of meat reduction to include in the decarbonisation path. As described in the proof of concept, we reduce beef and dairy consumption to a level, at which cattle in Luxembourg can be sustained in an entirely organic, grass-fed production system. Overall, this measure reduces beef consumption and dairy consumption per capita by 76% and 88%, respectively. Pork and poultry consumption are left unchanged. We have thus chosen an only moderately ambitious meat reduction intervention as a first step. Even at this relatively moderate level, the intervention reduces annual GHG emissions by 735,000 t CO2eq or 1.32 t CO_2eq. capita^{-1}.

Food waste accounts for 25% of food-related GHG emissions in Luxembourg and 33% globally, with about 52% of food waste in Europe occurring at the level of households, 19% in food processing, 12% in food service, 11% in primary production, and 5% in retail/wholesale (European Parliament 2017). Our intervention assumes that we can reduce food waste by 80% from 25% to 5%, through the following mechanisms: (1) weighing of leftovers in restaurants and canteens, combined to a software to analyse what guests eat least, in order to adapt portions, (2) introducing a "food bin" for households and restaurants/canteens that would be weighed and taxed accordingly (polluter pays principle), (3) promoting food donations of leftovers from stores, restaurants and homes to social and solidarity sector, and (4) running sensibilisation campaigns on food waste reduction. An 80% reduction in food waste would reduce per-capita GHG emissions by 0.5 t CO_2eq.

Consumption of goods, ranging from furniture to sports equipment, from consumer electronics to clothes, is commonly linked with income, and with GHG emissions. However, they will remain in use in a low-carbon world: books, bicycles, and clothes will not go away. While a significant share of consumption products today can be deemed non-essential (8.2 connected devices per person in Western Europe in 2019 (The atlas 2015), it is crucial to extend product lifetime by legislating on producer guarantees (e.g. Norway has enforced a 5-year compulsory guarantee on smartphones (Consumer Council of Norway).[15] Many more products could be repaired instead of thrown away, resold instead of deemed obsolete, and shared instead of individually owned for a combined 88% reduction in consumption. All in all, impacts from discretionary consumption could decrease substantially by 1.8 t CO_2eq. per capita under the sufficiency paradigm, without much loss of comfort for consumers.

Public services have a non-negligible impact, which is characteristic of high-income countries. Schools, universities, hospitals, but also government, administrative offices, police, firefighting, and defence infrastructure, can generate emissions as high as 1.5 t CO_2 eq. per person in 2020. The French think tank The Shift Project suggests that public administration should undergo massive changes in mobility (esp.

[15] https://www.forbrukerradet.no/cause-for-complaint/

commuting) and infrastructure (The Shift 2020) – in the present exercise, it could be expected that public employees indeed follow the same changes as the rest of society for a close to 90% reduction in GHG emissions. Administration and other public services need to show exemplarity: green procurement, radical commuting shifts for their employees, as well as regulating business travel, should be enforced rapidly and at scale in all the ramifications of the Luxembourgish public sector.

Decarbonisation of neighbouring electricity grids is scheduled to occur over the 2020-50 period. Since Luxembourg imports 62%, 20%, and 4% of its electricity from Germany, France, and Belgium (ILR 2020, and see fig.14) , emissions from electricity consumption in Luxembourg depend to a large extent on decarbonisation efforts across the border. According to these countries' electricity decarbonisation plans, emissions will be reduced by 80% and 67% in Germany and France, while emissions per kWh in Belgium are expected to increase by 25% due to the retirement of nuclear power plants. From the Luxembourg side, the intervention consisting of decarbonisation of neighbouring electricity grids is, though outside of our control (and unfortunate given the expected emissions increase in Belgium), nonetheless effortless, and we account for it in our decarbonisation path.

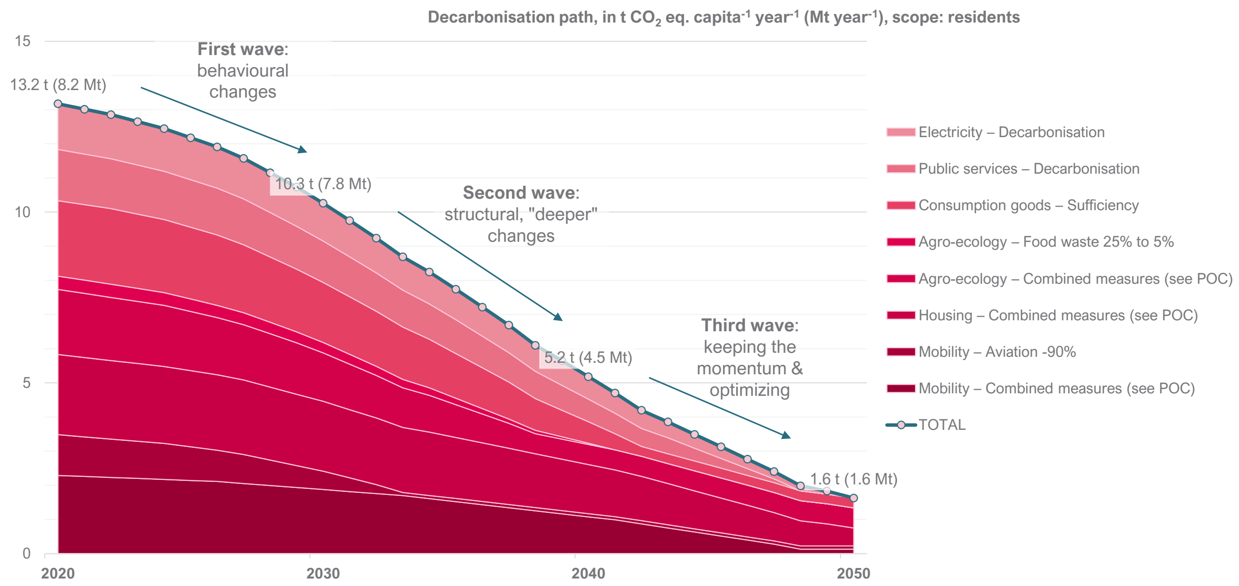


Figure 25. Timeline of interventions and resulting per-capita carbon footprint for the “residents” scope. The first decarbonisation measures will need to be behavioural, these include measures that depend mostly on behaviour and can occur without systemic change (diet, plane travels), followed by structural, deeper changes, and finally an “optimisation” phase, after which most impacts come only from essential needs, namely housing and food.
LIST calculations for LiT.

Decarbonisation timeline - Sequencing of interventions

Based on our absolute and per-capita decarbonisation path that we illustrate in figures 23 and 24, we have approximated the corresponding decarbonisation timeline (fig. 25) based on the speed or rate of implementation outlined in Table 4. In this phase of the proposal, the implementation rate for each intervention or combined intervention represents an approximation based on generally accepted implementation periods by type of intervention (infrastructure, regulation, behavior change). As mentioned above, we assume that regulatory changes can be implemented quickly, as political will is the only binding constraint. Behavioral changes follow in terms of implementation speed given the increasing exposure of the population in general to information on the threats that climate change poses to our wellbeing.

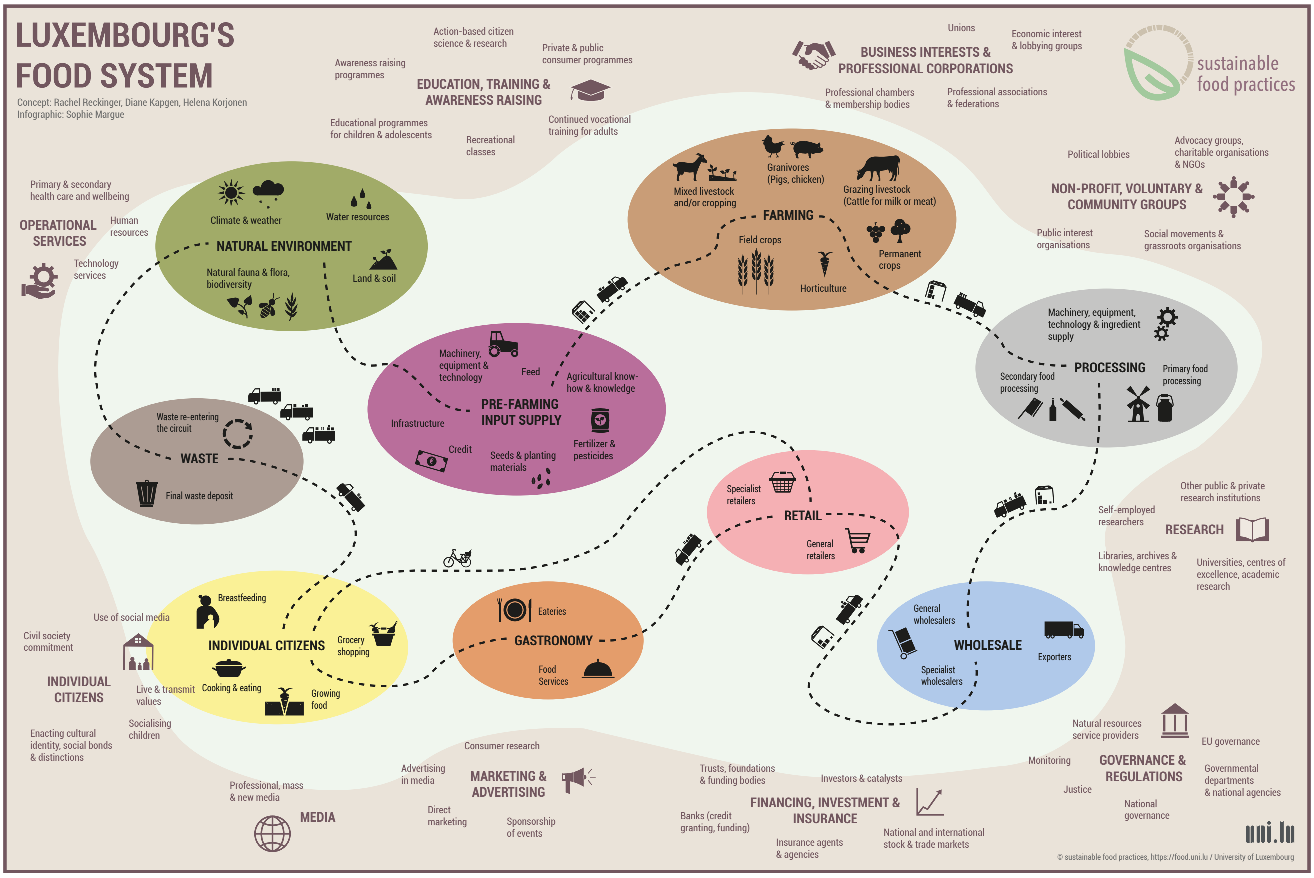
These kinds of interventions can be supported by regulations, such as subsidies for food donations to reduce food waste or taxes on air travel. Infrastructure investments have long planning and building lead times, and can prove particularly challenging in the Luxembourg context, since upgrades to the rail network need to be coordinated across the Greater Region. For some measures, notably the mobility intervention (POC), our timeline is based on more specific estimations by industry (Creos) for how quickly such a transition can take place. Taken together, our decarbonisation timeline shows that GHG emissions per capita decline slowly at first, when it is only the regulatory and behavioural interventions that are carried out, such as reducing air travel and meat consumption. This initial phase is followed by a second, steeper decarbonisation phase, when the more structural changes that require substantial infrastructure investments, such as energy efficiency improvements to the existing housing stock, are increasingly applied. We note again at this point that our proposal includes an ambitious carbon uptake target of 1.6 t CO_2eq. per capita in 2050 that fully matches the emissions target to achieve net zero climate impact.

03 Social and Ecological Resilience – for Humanity and for Decarbonisation

A common definition of resilience is the 'bounce back capacity' of a system, but in the context of current crises (climate change, mass extinction, coronavirus pandemic) where fast adaptation and systemic learning become indispensable, contemporary concepts for resilience rather call for a 'bounce forward capacity', i.e. for transformative resilience capable of pro-actively inducing disruptive changes that are necessary for its long-term survival, including changes in the institutional set-up (Giovannini et al. 2020). The common term to describe this situation is VUCA, an acronym that characterises the volatility, uncertainty, complexity and ambiguity of today's ecological, social, political and economic systems. According to the Post Carbon Institute, resilience should be built in communities rather than on a large scale or international level, because the community is the most available and effective level for intervening in human systems. It is at the community level that we interact most directly, both with people and with institutions. This argument holds true for many interventions that depend on behavioural change or local regulations, but larger shifts towards decarbonisation that affect natural monopolies, such as the transmission and transportation network, require intervening at the national and international level. For example, decarbonising transportation in Luxembourg requires coordination across the Greater Region. Our assessment of resilience focuses on all levels of government and society, from interventions targeting individuals or neighbourhoods to ones forging cooperation across the Greater Region and the world.

Our focus on resilience might seem out of place given the daunting task of reducing GHG emissions by almost 90% within 30 years. Nonetheless, a focus on social resilience is warranted given the indirect yet strong effect that economic and social wellbeing have on individuals' ability to reduce energy consumption and adopt behaviours that cost time or money but reduce GHG emissions. Investment in energy efficiency at the household level, for example, could suffer in the face of these constraints (Gillingham & Palmer 2014). Similarly, the upfront cost of reducing food waste, in the form of time and attention to change how frequently food is bought and cooked, could prevent families with fewer resources from implementing these changes, despite the adjustments actually saving them money in the long-run. Investment in personal health by eating well and exercising also requires time and money but reduces obesity and other morbidities, thereby decreasing demand for health care services and the health care sector's contribution to GHG emissions (Eckelman & Sherman 2016). Aside from the argument of supporting social resilience for its own sake, there is a case for increasing social resilience for the sake of decarbonisation.

The case for limiting our impacts on other environmental dimensions rests on the argument that the transition we embark on now is reversible only at high cost. We seek to avoid baking into our decarbonisation path unsustainability along other environmental dimensions that would need to be addressed at greater cost in the future. Again, sustainability in terms of marine and freshwater eutrophication, water and material use, local air pollutants, and biodiversity are worthy causes in their own right. We believe they have a place in our proposal for resilient decarbonisation, alongside the interventions that are geared specifically towards decarbonisation and which were presented in Table 4.



Coherence across interventions to meet the systemic challenge of resilient decarbonisation

Figure 26. Increasing the sustainability of Luxembourg's food system requires coordination across multiple actors and sectors. Such a holistic systems approach encompasses the food supply circuit as well as broader food system actors.

We take a systemic approach, in order to overcome disconnected and partly contradictory sectoral visions, resulting in narrow policies with partial results, that perpetuate structural blind spots. An empirically grounded analysis of the complexity of such a system has been done exemplarily for Luxembourg's food system (fig. 26). The holistic interdependencies that are shown among a wide set of actors not commonly thought of as taking part in a particular system – the food system in this example – can be transposed to a range of thematic fields characterised by complex networks, relations and influences, as well as governance structures at various scales. Our approach also emphasises traditional and new types of multifunctional land use as a means to integrate and synergise interventions across transition domains.

Table 6. Proposed interventions with a focus on resilience

Proposed interventions for resilience

Our proposed interventions with a focus on resilience are presented in Table 6. They are grouped by resilience domain, including social justice, collaborative and inclusive governance, ecological resilience, economic well-being, and public health.

Resilience in agro-ecology

Agro-ecology is defined in the following way: "Agroecology is an integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of food and agricultural systems. It seeks to optimize the interactions between plants, animals, humans and the environment while taking into consideration the social aspects that need to be addressed for a sustainable and fair food system" (FAO 2018). We use it here because it combines ecological and social aspects to agronomical ones. In the latter, it involves a systematic alignment to organic production methods, and beyond.

In order to attain the main objective of minimizing GHG emissions while satisfying certain environmental and social conditions, food sovereignty is the guiding operationalizing principle for the thematic area Agro-Ecology. Food sovereignty is defined as "the right of peoples and sovereign states to democratically determine their own agricultural and food policies" (IAASTD 2009). It should not be conflated with self-sufficiency rates on a given territory. More specifically, food sovereignty is "the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems. It puts those who produce, distribute and consume food at the heart of food systems and policies rather than the demands of markets and corporations" (FAO 2007).

It puts forward a strong participatory approach and equity considerations, by revolving around six principles: (1) food is not a standard commodity nor a component for international agri-business but a basic human right; (2) all the actors of food production chains, also marginal and vulnerable ones, are valued by appropriate policies; (3) providers and consumers are placed in the centre of decision-making on food issues, thus avoiding dumping of food as well as unsustainable, unaccountable and inequitable international trade; (4) instead of being privatized, control over territory, land, grazing, water, seeds, livestock and fish populations is given to local food providers, to be used and shared in socially and environmentally sustainable ways which conserve diversity; (5) skills and local knowledge of food providers and their local organisations are supported, developed and transmitted through appropriate research systems; (6) the contributions of nature are used in diverse, low external input agroecological production and harvesting methods that maximise the contribution of ecosystems and improve resilience and adaptation in a mutually regenerative way.

In order to secure these principles in a participatory way, with the double imperative of satisfying ecologically regenerative and socially equitable living conditions, a compelling, collaborative food democracy tool is paramount: the set-up of Food Policy Councils (FPC), uniting (1) individual citizens and representatives from civil society and from research; (2)

Goal	Intervention	Impact	Spatial implications and impact on greater region
Ecological Resilience			
Reduce use of pesticides	Prohibit (chemical-synthetic) pesticides of all kinds, incl. public and private use	**B**, LS, EQ	
	Promote agroecological techniques in private gardens	GHG, P, N, BW, CU, B	
Conservation agriculture	Use direct-seeding techniques into nurse crops as much as possible	GHG, N, P, B	
Optimisation of land use	Incentivise cooperative, regional bioenergy production factories collecting and exploiting biomass waste	**GHG, AP**	Changing land-use patterns, multi-functional space
	Use the freed-up arable land (ca. 70%) from animal reduction and feed-no-food policy in order to grow crops for innovative products (e.g. oat milk) directly for human consumption	**GHG**, **N**, **P**, B, CU	Changing land-use patterns
Promote animal well-being	Make enhanced animal well-being in animal husbandry mandatory (incl. Housing, transportation and slaughterhouse conditions)	**B**	Changing land-use patterns
Promote biodiversity	Increase share of agricultural area dedicated to promoting biodiversity	**B**	Changing land-use patterns
	Reduce the average plot size, to increase ecosystem diversity and promote species diversity	**B**	Changing land-use patterns
	Implement measures on the agricultural area to enhance the interconnection of areas for biodiversity promotion and/or ecologically valuable landscape elements	**B**	Changing land-use patterns
	Increase biodiversity on unbuilt urban areas by starting community gardens	B	Greener cities
Promote sustainable agriculture	Promote the use of dual-purpose breeds	**B**	
	Reduce the use of hybrids (both in animals and in plants)	**B**	
	Promote local and diverse seed production and multiplication	B	Changing land-use patterns
	Increase number of crops in crop rotations	**B, BW**	Changing land-use patterns
	Introduce a 100 % sustainability target for public food procurement (e.g. organic or better), measure sustainability based on True Cost Accounting principle	GHG, P, N, BW, CU	
Carbon Uptake			
Trees in agricultural and urban areas	Incentivise agroforestry, the planting of trees for carbon uptake on grazing land and on field edges	**CU, BW**	Changing land-use patterns, multifunctional land
	Incentive tree planting for carbon uptake in urban and residential areas	**CU**	Trees in urban areas
Increase carbon sequestration from forests and pastures	Increase the surface of forests and pastures	**CU**	Decrease of the buildable areas and transformation of grasslands, creation of cross-border topologies
	Improve management of forests to maximise their carbon sink potential	**CU**	Changing land-use patterns
Increase carbon sequestration by unsealing soil	Renaturalise surfaces of the fossil age (parking, brownfields, commercial zones …)	**CU**	Transformation of monofunctional areas, parking and brownfields into urban districts.
Increase soil fertility for increased carbon retention	Increase share of legumes on arable land and permanent grassland	**CU**, N, **B**	Changing land-use patterns
	Increase share of extensively managed grassland areas	**CU**, N, **B**	Changing land-use patterns
	Increase share of temporary grasslands on arable land	**CU**, N, **B**	Changing land-use patterns
	Increase share of arable land on which catch crops are grown	**CU**, N, **B**, **BW**	Changing land-use patterns
	Increase share of arable land with green cover outside of growing period	**CU**, N, **B**, **BW**	Changing land-use patterns
Optimisation of land use	Incentive multi-use of land, such as solar PV in agriculture (agrivoltaics), to reduce land take and increase forest	**CU, SS**	Multi-functional space
	Transform spaces (i.e underground parking, freed car spaces and last century infrastructures) that are no longer needed in their current form to reduce pressure on land use	**CU, SS**	Transformation of freed car parking spaces
Economic Wellbeing			
Increase self-sufficiency for more resilience in case of supply chain disruptions	Increase the diversity of locally produced food and reduce food importations		Changing land-use patterns
	Strengthen short supply circuits through food belts and multiplied food processing companies as well as distribution networks		Changing land-use patterns, green belts
	Foster food production and food processing areas in every neighborhood ("edible cities or villages")		Urban agriculture
Build a larger agricultural workforce	Create better incentives and facilitate access to land for young people and newcomers in order to promote farming as a vocation		
Increase of skilled workers	Upskilling of the construction workforce in energy efficiency and digitalisation		Attraction of skilled workers from the GR
	Create new transition professions (transition facilitators, catalysts, trainers...)		
Public Health and Nutrition			
Diversified, healthy diets	Promote flexitarianism (i.e. reduced meat consumption, combined with vegetarian and vegan diets)	**GHG, N, P, BW, B**	Change in logistics, adapted production sites
	Make cooking part of education curriculum, in order to learn to cook tasty and imaginative vegetarian dishes	SJ, LS	Multi-functional space
	Incentivise healthy food choices by making them more accessible (availability, affordability)	SJ, LS	Multi-functional space, make use of available land/ space: edible city, common gardens
Social Justice			
Equal access to high-quality foods	Introduce social policies to promote equal access to high-quality and sustainably produced food	**SJ**, LS	
	Develop & implement National Healthy Diet Plans (or 'Food Environment' Plans) incl. fiscal policies, social policies, public procurement, zoning & licensing, as well as nutrition education	SJ, DQ, LS	
	Exempt fruits & vegetables from VAT	**SJ**, LS, GHG	
	Ensure higher auto-production rates with the aim that households don't need to buy as much food	SJ, LS	
Build fairer international trade	Advocate for a UN Framework Convention on the Right to Food and on food sovereignty	SJ	
Social and cultural inclusion	Promote intergration of people of different social classes and backgrounds within neighbourhoods	SJ, DQ, LS	Inclusive typologies through urban granularities (urban island, neighbourhoods, buildings)
Access to energy for all	Ensure that energy expenses do not surpass a certain share of monthly budget	**SJ**, **LS**	
	Carbon fee-and-dividend need to be justly redistributive	**SJ**	
	Retrofit houses and provide adequate indoor temperature	SJ, **LS**, GHG	Visible construction only during renovation period
Collaborative and inclusive governance			
Collaborative governance bodies	Create a national Food Policy Council (FPC) based on principles of food democracy, to enable and ensure a democratic, horizontal, participative, multi-stakeholder strategy in the food system transition process	DQ, SJ, LS	
	Ensure an equitable rapport between this FPC and a national food policy, and link it to more local ones	DQ, SJ, LS	
	Ensure a democratic, horizontal, participative, multi-stakeholder dialogue in the energy system transition process	GHG, DQ, SJ, LS	
Create cross-sector and cross-border system innovation networks (IN)	IN for spatial justice, multifunctional land use & building retrofitting	GHG, SS, B, SJ, LS	
	IN for the energy transition	GHG, DQ, SJ, LS	
	IN for the regional circular and sharing economy	GHG, M, LS	
	IN for co-creation methodologies and participatory transition governance & monitoring	DQ, SJ, LS	
Citizen participation and empowerment	Create a distributed Community of Practice of professionals and a blended (on-line/on-site) delivery system for transition training & education (formal and non-formal) and new transition professions, for all age and target groups, for all transition domains & whole system, from basic to expert levels		
	Publish an inventory of existing initiatives (energy communities, prosumers associations, RE implementers, urban gardening, food coop., organic and local restaurants, food sharing, local seed production and exchange network)	DQ, SJ, LS	
	Promote citizen's involvement in local food production, processing and distribution	DQ	
	Support creation of repair cafes, shared workshops, FabLabs	GHG, DQ, SJ, LS	
	Support creation of citizen-owned energy coops	DQ	
	Educate citizens on energy use, basic knowledge of annual energy consumption	GHG, DQ, SJ, LS	
Public access to energy and environmental monitoring	Creos to publish hourly electricity consumption mix (as done by neighouring countries, see electricitymap.org)	GHG, DQ, SJ, LS	
	Promoting citizen science tools	GHG, DQ, SJ, LS	
	Enhance environmental education of citizens of all ages	GHG, DQ, SJ, LS	
Research-lead policies	Fund research on sustainable food systems, incl. regenerative agriculture and food sovereignty	GHG, N, P, BW, CU	
	Implement a research funding programme for participatory action research and citizen science projects advancing local transitions		
	Implement a new generation of transformative research funding programmes for each transition domain, incl. - participatory planning & multifunctional retrofitting - zero carbon community energy systems - sustainable and resilient food systems, regenerative carbon capturing agriculture & food sovereignty - regional sharing platforms & circular supply chains - participatory transition governance and monitoring		
Food literacy among all actors	Make Education for Sustainable Development programmes mandatory (incl. historical and current food imperialism in the Global North)	SJ	
	Include agro-ecology in educational programmes	GHG, CU, P, N, BW, AP	
	Train professional procurement actors to favour sustainable, high-quality, ethical foods	GHG, P, N, BW	
Policy coherence at system level	Ensure coherence across policy areas (environment, infrastructure, social, economic,…)	DQ, GHG	
	Coherence with Transition Pacts I and II, synergising Pacte Climat 3.0, Transition Hub projects and system innovation networks, while extending their reach across the borders into the functional region	DQ, GHG	Collaborate across Greater Region

Note: Indicators that we quantify are in bold. GR - Greater Region, GHG - greenhouse gas, N - nitrogen, P - phosphorus, AP - air pollutants, M - material use, BW - bluewater use, CU - carbon uptake, B - biodiversity, SS - soil sealing, LS - life satisfaction, SJ - social justice.

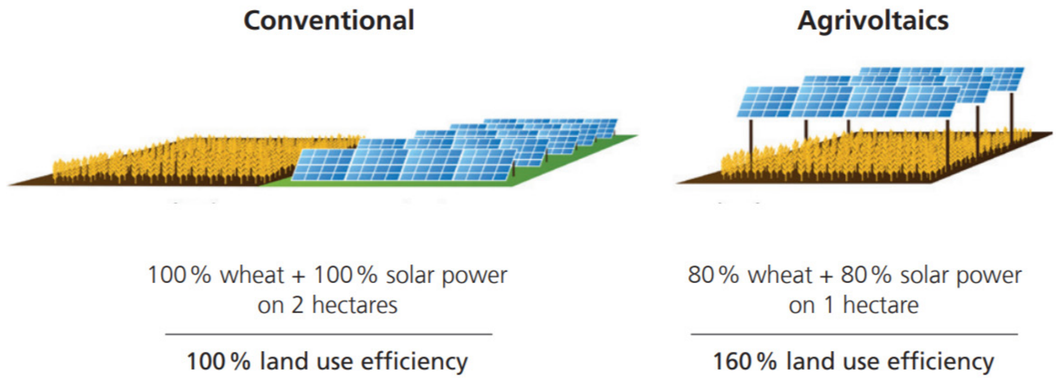


Figure 27. Schematic drawing and actual application of agrivoltaics in Heggelbach, Germany, at the Fraunhofer Institute test site.

representatives from the food economy (pre-farm input, production, processing, retail, gastronomy); (3) representatives from food policy and administration. Ideally, there would be one national FPC covering the national territory and the collaboration with the Greater Region, and several more localized ones. They would foster participation and food literacy among all actors in the food system, and ensure the application and respect of systemic ethics through all stages.

Optimising land use to increase carbon uptake and biodiversity

Reducing environmental impacts from agricultural production, such as eutrophication from nitrogen runoff or ecosystem vulnerability to pesticide impacts on off-target organisms, requires reversing the trend of agricultural intensification. Organic production systems that prohibit the use of synthetic mineral fertilisers and chemical-synthetic pesticides is one way of reducing environmental impacts at the local level, though it reduces yields by around 20% on average (De Ponti et al. 2012). This yield gap necessarily increases pressure on land use, unless it is accompanied by a change in diet. The rapidly increasing population in Luxembourg over our transition period and the need to build residences constitutes another increasing demand for land in Luxembourg. At the same time, the goal of our proposal is to preserve forest land, increase green space in urban areas, and not exceed the current area of sealed soil. One solution to meeting these competing demands for land is to increase the proportion of multi-use land.

Agrivoltaics, the combination of solar PV with crop or livestock production, has also been shown to increase land use efficiency. In Heggelbach, Germany, the Fraunhofer Institute tested a combined potato crop with an elevated solar PV system high enough to let farm machinery pass underneath. The land use efficiency in 2017 was 160% (80% potato yield and 80% PV yield) and increased to 186% in the hot summer of 2018 (fig. 27, Fraunhofer 2020).

Agroforestry, combining trees with crops or livestock on the same area of land, is an ancient practice that has gained renewed interest given the need to increase land dedicated to carbon uptake. A recent assessment of the productivity of agroforestry systems across Europe found that combined crop and tree yield in agroforestry outperformed those in monocultures by 37 to 100% (Lehmann et al. 2020). Examples include alley cropping systems with biomass belts of willow, hazel, and alder trees in Denmark, combined vegetable and biomass tree production in the UK with free-range hens for egg production, or fruit trees intercropped with vegetables in Poland. Thus, both agroforestry and agrivoltaics have demonstrated promising results in areas with a similar climate and soil type to Luxembourg.

Resilient and Regenerative Cities

Architecture and construction, and a particular focus on the regeneration of the existing building stock is another area of focus both in terms of decarbonisation and resilience. Amongst other interventions, there is a large opportunity to tackle the building-related emissions per capita by improving the energy efficiency of the existing building stock (e.g. in the UK it is considered that 80% of the building stock in 2050 is already built). Moreover, developing architectural patterns supporting densification while avoiding soil sealing, such as through extensions to use rooftop space, can have a significant impact. A careful analysis of the rooftops potential to host either 1) energy production systems (photovoltaics), 2) urban farming/agriculture (including communities gardening) combined with 3) additional floors and dwelling space through lightweight construction systems (which ultimately leads to new property revenues enabling the energy-efficient upgrade of assets) will be performed in Stage 2.

Urban heat islands are a typical feature of the urban climate. They are characterised by the difference in air temperature between the cooler surrounding countryside and the hotter city centres and can reach up to 10 Kelvin during night-time under cloudless and calm weather conditions. The elevated air temperatures in cities depend strongly on the building geometry, the thermal properties of material of the building, radiation properties of the urban surfaces and anthropogenic energy release, e.g. domestic heating, traffic and industry emissions. In consequence urban inhabitants – especially older people, people with existing conditions, e.g. of the cardiovascular system, and small children – are exposed to greater risks of heat stress. Especially during heatwaves, the higher temperatures in cities lead to a greater use of cooling and air conditioning systems and thus to a greater consumption of energy.

Urban greenspaces (green infrastructure) can provide a significant cooling service, which extends beyond the greenspace boundaries. They include networks of urban trees, private and public greenspaces like parks, gardens, playing fields, and green corridors, as well as green roofs and walls. Consequently, greenspaces are recognised for their ability to locally reduce the urban heat island and thereby positively affect the thermal comfort and health of urban citizens. However, the amount of cooling provided by a greenspace and the distance over which that cooling extends depend on factors such as greenspace size and characteristics. The relation between cooling effects, distance to the urban parks and the size of the parks for a European city (London) is given in figure 28.

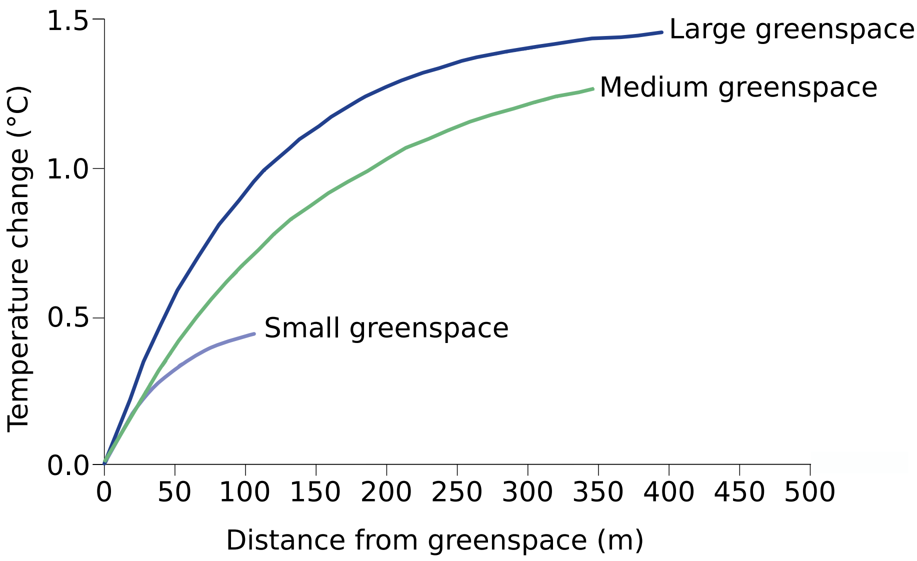


Figure 28. Estimated air temperature increase with increasing distance from urban parks of different sizes (small: 2.5 ha; medium: 12 ha; large: 111 ha) under cloudless and calm weather conditions (Doick et al. 2014; Monteiro et al. 2016)

The primary objective of cold air corridors is to facilitate air exchange in cities, thereby enhancing the potential for cool air flow from the surrounding hills towards urban areas. Through green ventilation corridors and construction bans at strategic places, it is possible to hinder overheating of the inner-city centres, especially during nights, improve air quality and increase resilience against global warming. Depending on the topography and the meteorological conditions, thermal winds with different intensities are created. In order to investigate and quantify those climate and emission-ecological functions the ClimFun project was funded by the MECDD in Fall 2020. Using the numerical model FITNAH-3D the following paraments will be calculated: Biometeorological indices like Physiologically Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI), air flow velocity and direction, cold air production, volume of the cold air flow, and cold air drainage flows into the urban housing areas. Model output will be available for the whole area of Luxembourg in March 2021 with a spatial resolution of 25m-length grid cell, enabling the integration of the model results in concrete urban planning processes in order to improve local air quality and enhance the biometeorological condition including health effects.

04 Challenges and Limits of the Exercise

Sustainable development is a very complex process that cannot be represented, in its multiple features, by only one indicator. This was the ultimate reason to consider the multiple dimensions of the Doughnut, as well as the ecological footprint and ISEW, as additional metrics to check the evolution of the GHG emission reduction trajectories. We proceeded in this way to avoid generating significant other environmental and social problems, from a life-cycle perspective, while decreasing carbon emissions However, the assessment of these multiple dimensions has several limitations, both from a methodological and data standpoint, as previous studies have also shown.

Environmental ceiling

All of the indicators, including GHG emissions, are calculated using the multi-region input-output (MRIO) table model EXIOBASE 3.8. This is a reference model and database used for environmental accounting, among several others which share the same methodological basis but different assumptions, data sources and calculation procedures. As such, a variability (uncertainty) in the calculation of the indicators is expected. However, general deviations of footprints based on MRIO do not exceed 15% across MRIO databases for a large number of economically important countries (Giljum & Palmer 2019).[16] Moreover, data differences in sectors, which receive materials at later stages in the supply chain, such as manufacturing or services, generally have only a minor impact on demand-based material flow indicators. This pattern was observed for all selected countries, that is, developed countries and emerging economies alike. As Luxembourg consumption falls within this case, a maximum error of 15% is expected.

As the environmental ceilings are considered independently of each other, trade-offs and synergies between environmental mechanisms are ignored. Environmental compartments are linked to each other, e.g. net CO_2 emissions can ultimately affect bluewater consumption (Arbault et al. 2014). Therefore, downscaling boundaries from the global planetary scale to a specific sub-planetary scale like the one of the Luxembourg territory does not fully reflect its specificities.

The allocation of environmental ceilings from the global scale to the per-capita national scale was done by averaging based on population, which does not reflect territorial and social segmentation specificities. At the global level, there are major discrepancies between countries when it comes to current emissions levels and quality of life, which shall be reflected in the ceilings attributed to each. Similarly, differences can be observed at Luxembourg level, between the poorest and the richest inhabitants. While we have taken care to select indicators and ceiling levels that are relevant to Luxembourg, there is still only a single target for the whole country. The averages considered shall be interpreted further in light of these considerations in the further steps of the study.

The air pollutants ceiling is understood at global level, i.e. representing the human health damages resulting from the accounting of world emissions of several combustion-related air pollutants (NOx, SOx, particulates) in all economic sectors affected by Luxembourg's consumption. As such, specific (local) pollution peaks in Luxembourg are not considered in our analysis and cannot be related, in a quantitative manner, to the planned interventions (e.g. CO_2 emission reduction trajectories).

We measure material intensity by summing the material weights across several different types, such as iron and wood. As the environmental footprint "rucksack" of different materials does not correspond to the densities of the materials, our measure does not accurately capture the impacts of our interventions on critical materials. Our indicator must therefore be considered as an intermediate proxy of the intensity of material use by Luxembourg society, following the reasoning that "less is better" and not considering (at this point) possible trade-offs and optimisations across different materials.

[16] The limits of the exercise when it comes to the complexity of a territory, methodological challenges and data gaps.

Social and environmental foundation

Climate regulation is an essential component of resilience and potentially a significant contributor to decreasing the net CO_2 balance. However, its calculation depends on the modelling of land cover changes and CO_2 uptake by different land covers. As outlined in Othoniel et al. (2019), to improve the modelling of cropland and grassland, the granularity of these classes could be increased, i.e., cropland could be divided into rapeseed, maize, wheat, etc., and grassland into natural grasslands, pastures and meadows. As a result, the land use model should better simulate the land covers that are dedicated to agricultural uses. For simulating the expansion of forests, we encountered the issue that this type of land cover did not substantially expand in the past. Therefore, we had little information available to calibrate the model. In fact, this remark applies to all land uses in Luxembourg. Because relatively few land use changes occurred in the past, there is a weak signal to interpret, which is always more difficult to simulate. On top of this, more accurate land use data could be used, for instance from direct observations.

Our measure of biodiversity is specific to agriculture, with the advantage of capturing the impact of Luxembourg agricultural production across farms on multiple dimensions of biodiversity and the disadvantage of not capturing impacts from other sectors, such as housing and infrastructure, on biodiversity. Nevertheless, agriculture is the mechanism through which we interact most directly with nature, and we choose to measure the impact of our interventions on biodiversity in a more specific albeit narrow way.

Life satisfaction and social justice are extremely important social indicators to check that GHG reduction trajectories do not ultimately result in lower well-being, despite the positive indirect effects qualitatively described in terms of living, mobility, housing and access to locally sourced food and healthy diets. Their quantitative assessment, in relation to the planned interventions, is however a very difficult and resource intensive exercise which can only be done partially within the limits of this study. In particular, life satisfaction is only based on a few drivers of the PIBienÊtre and we are therefore unable to fully consider the social effects of the interventions.

Ecological footprint (Galli et al. 2016)

As stated by the Global Footprint Network, “the Ecological Footprint (EF) is not a measure of human impact, nor is it a predictive measure of the sustainability of specific management practices. It is an accounting system that compares human demand on Earth’s ecosystems to what these ecosystems are able to renew” (Lin et al. 2015). It remains however a powerful communication tool. For these reasons it is included in this study as an additional indicator to check our trajectories and communicate on these.

The EF equates “agricultural productivity” with “Biocapacity”. However agricultural productivity is increased by use of non-renewable fossil energy and monocultures (contributing to soil erosion, the use of pesticides, phosphorus and nitrogen emissions to the water, and biodiversity loss). The environmental footprint of these components is not captured by the

EF, though it is included in the corresponding Doughnut dimensions. In its accounting system for CO_2 capture, the EF ignores that a forest area can absorb emissions only during growth. When the forest becomes mature additional forest area is needed.

Index of Sustainable Economic Welfare (ISEW)

The ISEW has the advantage of measuring sustainability in monetary terms, which is widely understandable by non-experts. For this reason, it is considered alongside the EF as a communication tool. However, monetary units are unstable predictors of the future as they can fluctuate by orders of magnitude. Also, indicators in monetary terms show current human preferences in the market, not ecological necessities, or resource limits. As such the ISEW cannot establish clear ecological limits to demand and does not deal with trade, as EXIOBASE does.

III. PROSPECTS

01 Our Posture towards the Socio-Ecological Challenges

Our proposed decarbonisation path would change fundamentally how we lead our lives, from where we live, how we work, and how we move, to what and how much we consume, and how we spend our leisure time. The required interventions have several themes or overarching principles in common: a) sufficiency or a post-growth perspective, b) spatial justice as the consideration of social justice and social inclusion in cross-border spatial planning, and c) regenerative development in general, and urban regeneration in particular.

These principles were used as underlying guidelines in constructing our initial set of interventions, from which we selected those that form our decarbonisation path. In pluralistic societies, design and assessment of sustainability transitions necessarily unfold in a contested space of values and worldviews (Meinhertz et al. 2020). There is no neutral position. The formulation of our objective function to minimise GHG emissions per capita given certain environmental and social constraints is in a certain sense already a reflection of those values, though the assessment exercise itself is by construction dispassionate. The creation of this set of interventions and the selection of interventions for our decarbonisation path can thus be deemed both a values-based and science-based exercise.

Post-growth and sufficiency

One central pillar of our posture concerns the need to overcome the economic growth fixation of the current socio-economic system. We build on post-growth-oriented approaches that seek to establish alternative types of production, consumption, mobility and housing that are a) leading to reduced material and energy use, and b) dissociate well-being from market and financial mechanisms that imply continuous growth (Demaria et al. 2019; Hickel 2019; Schmelzer & Vetter 2019; Schmid 2019). In search for this “prosperity without growth” (Jackson 2009), spatial development policies in general, and spatial planning and design at all scales in particular may play a fundamental role.

The understanding of post-growth discussed in the research community is sometimes misrepresented in political and media debates. Post-growth is not meant to be the opposite of growth, i.e. post-growth does not imply shrinkage (e.g. of the population) or decline (e.g. economic recession). Rather, it pleads for a rethinking of current production systems and consumption patterns predominantly marked by a strive for ever more – nurtured by prevailing tax incentives and dynamics of lending and interest schemes. It also starts from the observation that – despite all efforts of so-called green economy approaches – efficiency gains in material use and energy consumption have not led to an absolute decoupling of resource use from economic growth (Paech 2010; TU Wien 2019). This is partly due to direct or indirect rebound effects (also Jevons Paradox), when efficiency gains are overcompensated through increasing consumption of that same good or through other energy intensive activities. The latter can also be related to a one-sided belief in technological advances as the primary solution strategy as seen e.g. in Smart City/Smart Home approaches (Hobson and Lynch 2016; Kenis & Lievens 2016).

Recognising the limited effect of interventions that focus solely on efficiency and technology-oriented strategies, a more disruptive reorganisation of the economy is necessary, since many of our interventions involve actually reducing consumption. This plea has started resonating beyond degrowth activists or academic circles, as for example Tim Jackson's report for the UK government cited above (Jackson 2009) or the fact that the EU parliament hosted a larger post-growth conference in September 2018 (Bauler 2020). Two guiding principles follow that differ from green economy and sustainable growth strategies propagated by the United Nations or the EU: First, a common good orientation that helps distinguishing business models that primarily serve societal well-being from mere profit maximisation objectives. And, second, a strive for more sufficiency-oriented practices that go beyond the adaptation of individual lifestyles and discuss sufficiency as a societal goal needing democratic legitimisation, political support and effective regulation (Schneidewind & Zahrnt 2014). Against this backdrop, we assume that a reorientation towards post-growth objectives is the most promising avenue for the socio-ecological transition and therefore will gain momentum in the future – with manifold implications for spatial development (see the draft of our vision for more details).

A post-growth regime will generate a series of new or adapted spatial practices, ranging from different forms of work organisation and mobility itself to an expansion of the rail network across the Greater Region, a reduction in energy consumption, a reorganisation of land use in agriculture, and new housing typologies. They all will impact the spatial organisation and thus call for adapted spatial planning policies and principles. Obviously, these trends will challenge the role of spatial planning in many regards. Post-growth planning goes beyond the topical reorientation (Lamker & Schulze Dieckhoff 2019; Brokow-Loga & Eckardt 2020; Schulz 2020). It includes new ways of evaluating (objectives/guiding principles), monitoring (indicators) and coordinating spatial development. The latter encompasses a revision of planning procedures towards more inclusive and participatory decision-making processes, which goes hand in hand with a redefinition of the planning professionals' self-understanding towards a more immersive role, moderating between different interest groups.

Post-growth implies including sufficiency in the policy and practice mix. Sufficiency-related interventions include changing eating habits; reducing overconsumption and waste, intentionally reducing consumption of consumer goods; choosing the right size, dimension and power rate when buying equipment; adjusting level and duration of use of an equipment to real need, sharing the use of an equipment among several users; reducing distances needed for the same service; new organisation of services; adaptation of production and distribution networks; better adaptation of vehicles to their use (size, weight, speed...); reducing the surface per person in housing (priority to smaller housing units with generous shared spaces, cooperatives and co-housing) as well as in office and commercial buildings, using more shared spaces, using them in alternating ways more continuously (Kuhnhenn et al. 2020).

Sufficiency at the collective level

In the context of this 'Luxembourg in Transition' call, the main emphasis should be made on the political response towards a real system change as a prerequisite for a substantive decarbonisation. Focusing on individual reductions takes attention away from the need to ensure adequate energy services for everyone. Sufficiency encompasses concerns for social wellbeing and equity: “Good politics creates the room where the Good Life can be lived” (Schneidewind & Zahrnt 2014). The role of the political level is to set the frame for the right measures for time and space, for property and the market. It can mean ‘less’ (having less and doing less), but it will also sometimes mean ‘different’, sometimes ‘better’, and sometimes ‘finer’. Wolfgang Sachs introduced the concept of sufficiency into the sustainability debate in Germany at the beginning of the 1990s. He encapsulated it in four principles to serve as guidelines in the search for the right measures and strategies for sufficiency: in time ('less speed’, meaning more slowly and more reliably), in space (‘less distance’, meaning closer and clearer), in the material world (‘less clutter’, meaning simpler and fewer), in the economy: ‘less market’, meaning providing and making for oneself).

As sufficiency policies are key for addressing the climate crisis and the lack of resilience at the state level (Loske 2018; Linz 2015), there are a number of tools and measures to address sufficiency on a public policy level (Linz 2017). The right conditions need to be put into place, by the creation of a more urban habitat, a largely electric, service-based and collective mobility, an infrastructure to reduce food waste in supply chains and the food service sector, a circular economy in both consumption and production patterns, practically free of fossil fuels, cutting final energy consumption to less than 50% of the current level and a fiscal system that is adapted to the transformation. The development of so-called convivial technologies (like fab labs, maker spaces, low tech labs and repair cafés) needs a setting of basic space (conceptually), places (infrastructure) and cultural change (experiences), and there needs to be a commitment (pacts). Also, a number of core dimensions need to be addressed in planning: relatedness, accessibility, adaptability, bio-interaction and appropriateness (Vetter 2017).

Sufficiency at the individual level

Lifestyles in which users consume fewer goods and services, have the potential to make a considerable contribution to decarbonisation (Faber et al. 2012; Millward-Hopkins et al. 2020). The decision to consume less even if we have the means and desire to consume more is a difficult one, and the required behaviour changes at the individual level will come about only through public information campaigns and a change in culture. This does not mean such changes in behaviour will never come about. The Covid-19 pandemic has shown how radically we can change our lifestyle even on a voluntary basis, if called upon to do so. On an individual level, sufficiency relies on a personal and voluntary approach, and is akin to a philosophy of life, such as Pierre Rabhi's "happy sufficiency" (*sobriété heureuse*) where moderation of our needs is a step towards individual fulfilment (Rabhi 2010). It differs from austerity because it is not badly lived, it is a personal self-limitation of consumption inscribed in a path of fulfilment. Achieving this neutrality in GHG emissions is also socially desirable because the necessary changes lead to healthier lifestyles than today, or even more comfortable ones. It is also constructed as a reaction to the imaginary of happiness through consumption. It is therefore a change of value system, a shift from material overabundance to material sufficiency, from property to shared services, from a society of speed to projects of deceleration (slow life, slow food, slow trip).

It can be expected that there are roughly 3 levels of personal motivation that would remain unchanged between now and 2050 (Laurent 2020): the 'drivers' as 20% of households who see the proposed changes as an opportunity to put their values into practice and who value sufficiency in itself; the 'variables', with 60% of households deploying differentiated, resistance or participation strategies according to their life phases; and the 'reluctant', 20% of households who consider that any change is an attack on their comfort and preferences. While Luxembourg's inhabitants seem to be sceptical that a lifestyle change might really work, 73% declare to be ready to contribute to a major shift (Atoz 2019). And in the context of the recent pandemic situation, 84% are opting for slowing down the pace of society (Mouvement écologique 2020).

Spatial justice

Our second cross-cutting guideline is spatial justice, understood as the "equitable spatial distribution of resources and opportunities, fairness in relations of power that shape social relations" (Madanipour et al. 2017). We are not only interested in the transition towards a decarbonised economy, but also in ensuring this process is equitable. How does such a transition allow a fair distribution of resources in space and how and with whom will transition pathway, intervention and monitoring decisions be taken?

The current growth paradigm produces spatial and social disparities, e.g. between rural and urban areas, between the neighbourhoods benefitting and those suffering from heavy industrial and transport infrastructures, between municipalities on either side of the national border. The ecological transition will require adaptive measures, new decision-making practices and governance structures, as well as substantial changes in planning to address issues of equity and justice intrinsic to the transition pathway. The transition requires not only to be socially accepted, but also to be thought and embraced by all social groups within the Luxembourg functional area, which is why focus group discussions on our proposed decarbonisation path with residents on both sides of the border form part of our proposal for Stage 2. For such a regional transition to occur equitably, governance needs to be adapted to minimise the production of disparities. It therefore requires to be thought and implemented for all those living and working in the functional area.

Spatial justice is a relatively recent concept having emerged in geography and urban studies. It originated from radical thinkers like David Harvey (Harvey 1973), Henri Lefebvre (Lefebvre 1974) and Edward Soja (Soja 2010) to problematise unequal access to resources and opportunities in the urban context. In parallel, the notion of environmental justice emerged in the USA, first in reaction to the racially motivated distribution of industrial pollution and waste. Then, this literature incorporated the distributional patterns of an expansive range of both environmental 'bads' and environmental 'goods', transcending also ethnicity, race and including social differences (see Davoudi & Brooks 2013 for a review). The relevance of this approach has been emphasised more recently to analyse debates on climate transition, energy transition (Heffron & McCauley 2018). The spatial, environmental and climate justice strands of the literature share their attempt to identify the fundamental sources of injustice and to use justice as a transversal conceptual and operational tool allowing to "unmask the exclusionary effects of a fixed concept of space, hierarchy, identity or authority" (Barnett 2015). They often use distributive and procedural mechanisms as corrective tools to injustices.

Our vision of the ecological transition is equipped with spatial justice as a conceptual and methodological tool to conceive a spatially just transition for those living in the Luxembourg functional region and on the planet, so that the country's contribution to global GHG emission reductions is fair. Our vision is also in line with the current conceptualisation of the European Green Deal which aims at reaching climate neutrality by 2050 in a "fair manner" (EC COM(2020)460), operationalised both with distributive (i.e. "just transition fund") and procedural mechanisms (i.e. "active social dialogue", European Commission 2019).

The operationalisation of spatial justice in the Luxembourg functional area requires a dedicated conceptualisation. Classically, the notion of justice is circumscribed by and within a bounded identifiable political entity. This is central as justice is exercised by a polity for a specific community of people. This has two important consequences: it "transforms a mass of individuals into a political community" (Davoudi & Brooks 2013) and legitimises, justifies political authority and political obligation. The "cross-border metropolitan area around and including Luxembourg" is a functional area. Even though it "gives rise to strong interdependent relations between the territories located on either side of the state borders" (tender, p.42), illustrated by growingly diverse social practices (e.g. work, leisure, housing), it is far from constituting a political community. This would go beyond the ambitions of the interregional cross-border cooperation established in the Greater Region.

In addition, the spatiality of this functional area is fluid, constantly evolving in time and space with the intensity of cross-border interdependencies. Establishing a dedicated institutional setting to bound this spatiality would therefore be vain. European border areas are, by nature, transcended by contradictory territorial logics – the Member States' striated territoriality and the soft and mobile European territoriality. Yet, taking this cross-border spatiality as a starting point to think and operationalise the ecological transition is certainly the most legitimate one, as it is where people are the most affected by this transition. This gives them not only the right to have a say but also a responsibility to contribute to this transition. This ecological transition will have impact at the national level but also at the local and cross-border level. It may also have uneven geographical effects, from positive to adverse effects in some areas and on some communities or social groups rather than on others.

The principle of all affected interests supports the extension of democratic politics beyond the boundaries of inherited political communities with the modern state (Barnett 2017). This allows focusing on non-institutionally defined areas guided by “a form of inquiry focused on understanding the articulation of experiences of the injustice of domination through the processes of claims-making and public formation” (Barnett 2017). With this approach, justice is thought as the ability to define and shape one’s own destiny. This allows considering spatial, climate, environmental and social justice together.

Participation and capacitation are paramount for the communities of the Luxembourg functional area to be able to effectively shape their own future. We understand participation and capacitation as a means for them to have an equitable say in the ecological transition, to effectively take part in it and benefit from it in a fair way. These two approaches are not only relevant for individuals, but also for the public authorities, private companies and civil society initiatives. The ecological transition can only be effective in this territory if most individuals, groups and organisations feel concerned and become actively involved. This guideline can be specified around three main segments: tools for distributive justice, procedural justice, and the combination of both.

Firstly, the implementation of this vision requires setting-up – and aligning existing – incentive schemes so that the impacts of possible adverse effects on the most affected spaces and communities are addressed. This priority would allow equitable distribution of resources in space.
Secondly, the implementation of spatial justice requires tailored participation schemes at the level of the development of the vision and at the level of local implementation (e.g. for individual projects). Participation mechanisms are an empowering tool to make the transition not only equitable but also effective. It allows also taking effective account of vernacular knowledge, complementary to technical and scientific knowledge, thus implementing place-specific projects.
Finally, distributive and procedural tools are conceptualised together as processes capacitating the public and private spheres as well as the individuals, allowing effectively the territory to be “re-appropriated, restructured and re-inhabited” (tender, p.43). Effective autonomy of sub-national authorities is paramount, and processes enabling local development actions are essential to this endeavour. In complement to these aspects, taking the ecological transition seriously requires constant reciprocal and consistent (re)-articulation with the cross-border planning scheme and other relevant sectoral policies.

Figure 29. Participatory learning in a permaculture course 2014 on the site of TERRA, the first community supported agriculture project in Luxembourg, which is part of the Transition network.

Regenerative sustainability and urban regeneration

Regenerative sustainability is based on the idea of doing “more good” than just sustaining the existing system, as opposed to current sustainability, which is based on the idea of doing “less bad”, i.e. reducing harm caused by default (Brown 2016). While restorative implies restoring social and ecological systems to a healthy state, regenerative enables social and ecological systems to maintain a healthy state and to evolve (Wahl 2016). In the eyes of regenerative design, human and natural systems actively co-evolve as one integrated socio-ecological system.

Regenerative development in the most recent and advanced understanding means, accordingly, to develop first of all “the strategic, systemic thinking capacities and the stakeholder engagement required to ensure the design process achieves maximum systemic leverage and support. To that end, it integrates building, human and natural development processes within the context of place” (Mang & Haggard 2016). Systemic thinking is the analytical approach by which the attention is shifted from the study of single events to the study of the systems from which they emerge. This means no longer looking simply at causes, effects or correlations in single dimensions, but instead at complex spatial and temporal patterns, established but also emerging structures, and the so-called leverage points (Meadows 1999). Leverage points are places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in one thing can produce big changes in everything. Leverage points, therefore, are very important when seeking to generate change in interconnected ecological, social and economic systems. Harnessing the leverage points often means discovering and changing the mental models underlying our collective practices. The mental models we will question and change are those listed and described in figure A4 in the annex.

A leverage point methodology can also be applied for systemic urban regeneration in highly contextualised and place-specific ways (De Flander & Brugmann 2017). Urban regeneration (*urbane Transformation* in German and *renouvellement urbain* in French) goes back to the neo-rationalist movement of the late 1960s and 1970s, when, following the functionalist dogma of tabula rasa, the existing (and later mainly historical) urban structure was considered fertile as a reservoir for further planning (Rossi 1966). The motto of carefully renewing cities (*behutsame Stadtreparatur*, *Reconstruire la ville point par point*) rather than renovating them through demolition and new functionalist construction was not initiated without conflict by alternative citizens' movements or progressive city administrations alike in Bologna, Paris, Berlin and many other cities in Europe and the USA. The extent to which urban repair takes place on the two levels – official architectural discourse and citizens' movements – can be seen for the first time at the IBA Berlin 1987, which had a new-building section where the critical reconstruction of the urban morphology was at stake, and an old-building section where the inhabitants of the historic building fabric could regenerate their living biotopes with the help of experts (Hertweck 2020b).

Finally, in the course of the 1990s, the ecological component of urban repair became more explicit as the environmental benefits of improving existing urban areas were recognised. Not only the idea of the city of short distances, which was promoted through urban and architectural mixing and the deconstruction of non-urban infrastructures, but also the importance of metabolic urban-rural systems (as opposed to compact cities with intense heat islands) became increasingly important. The concept of the *Zwischenstadt* (Sieverts 1997) and the experimentation with it in the context of the IBA Emscher Park (1989-99), where regeneration was transferred from the inner cities to industrial urban landscapes, was ground-breaking in this context. In recent years, urban regeneration has increasingly focused on the challenge of climate change, alongside community-based and urban planning issues, especially in light of the transformation of many growing cities into pyramidal cities with a weak periphery and high traffic volumes. Speculation with land stands in the way of inner development that strives for social and functional mixing (Hertweck 2020a).

We are taking up the principle of moving away from building on greenfield sites, while following the idea of regeneration on two levels: first, in existing cities, which we regenerate so that they become functionally and socially diversified by transforming office space, which starts becoming vacant, and by building on the top of existing buildings and not on vacant lots as our aim is to keep a high degree of porosity. Second, regeneration occurs on the land and structures of the industrial and mass consumption society, which we partly naturalise, partly transform into intermixed urban neighbourhoods. The participation of citizens will be central: in political decision-making processes, especially with regard to urban development, in the co-design of residential buildings (not only in building cooperatives, building communities, also in innovative social housing), as well as in the design of exterior and interior spaces, in which the elementary structures are fixed (plots, prefabricated and recyclable skeletons, multifunctional shafts) allowing for great flexibility in granular make-up and use which can be easily changed over time.

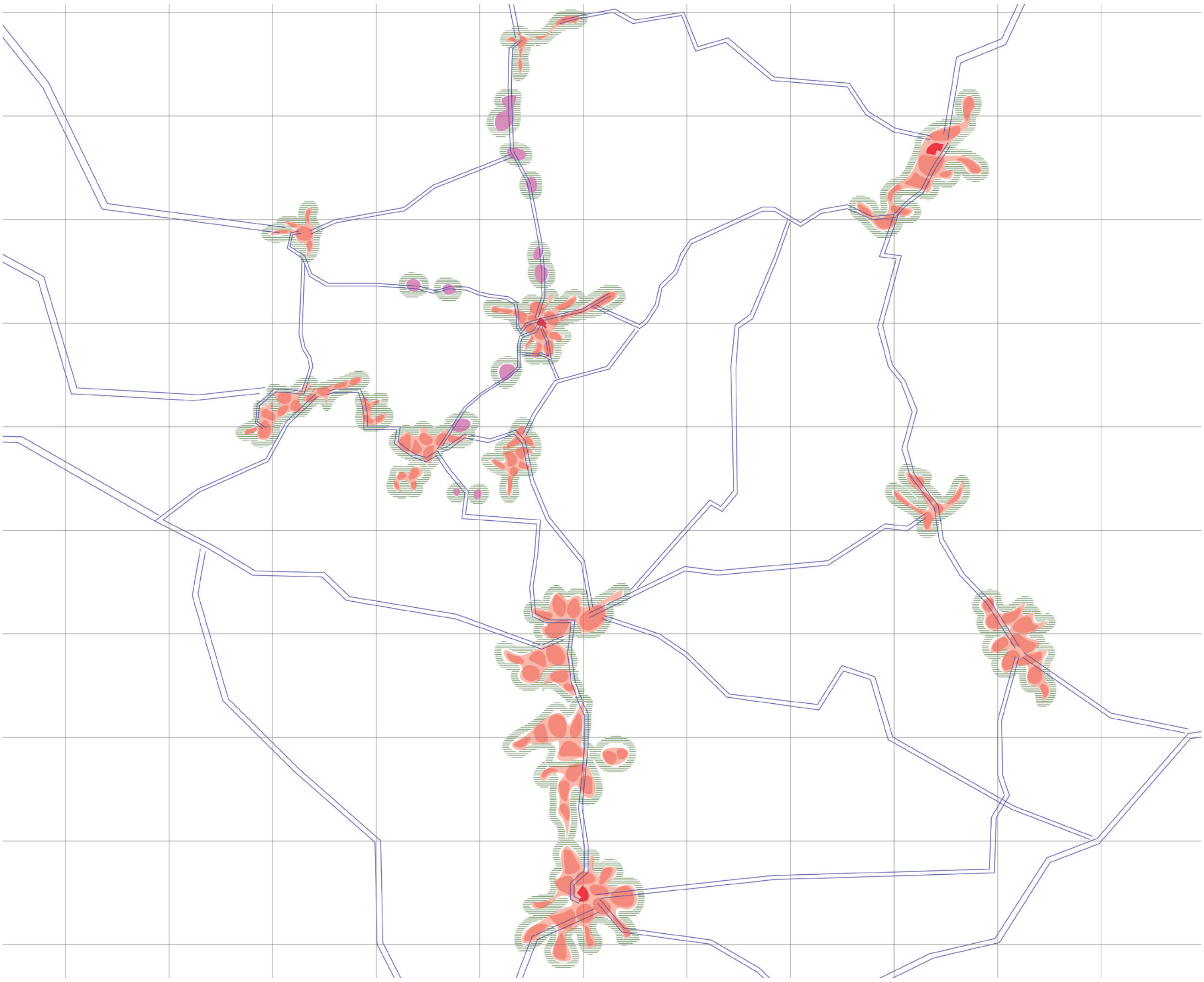
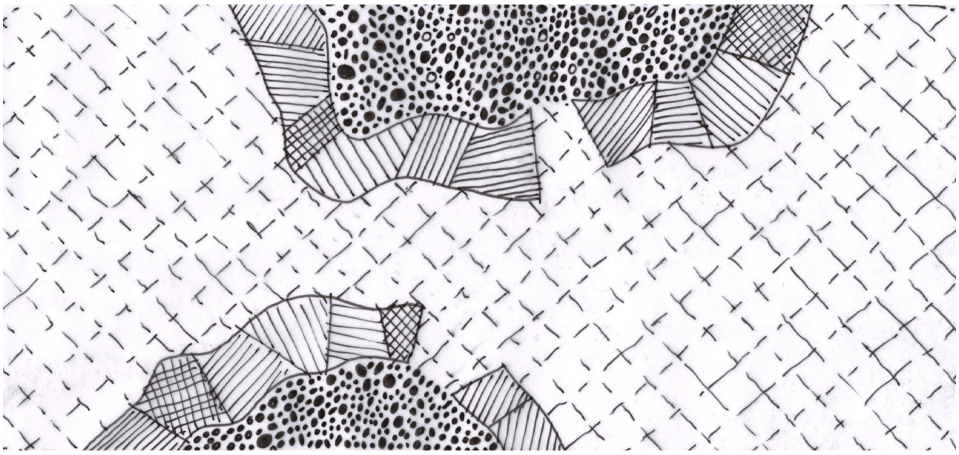


Figure 30. Sketch of the Regenerative City-Landscape

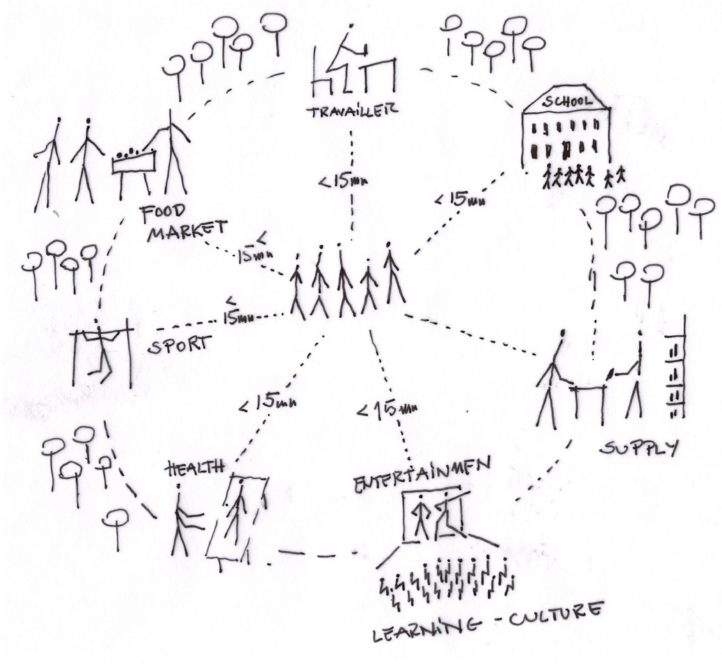
02 Eight Prospects for Luxembourg 2050

We lack narratives that tell us what a low carbon world full of resilient communities would actually sound, smell, look and feel like. We are capable of dramatic change, argues Rob Hopkins, co-founder of the Transition movement, but we fail because we have largely lost our most important tool: the human imagination, the ability to look at things as if they could be different and ask: what if? This is likely to be the most revolutionary yet crucial question of our times, and it is one that has guided our research in this report for a decarbonized, resilient and regenerative Luxembourg 2050. Below we attempt to answer this bold question and present what Luxembourg could look like in 2050, if the interventions we propose for our resilient decarbonisation path would come to fruition.
The following description of Luxembourg in 2050 is the intermediate result of previous works, collective brainstorming and two internal symposia. It will serve as a basis for the second stage, where we intend to complexify, conceptualise, spatialise and design the vision in the territory.



A Regenerative City-Landscape

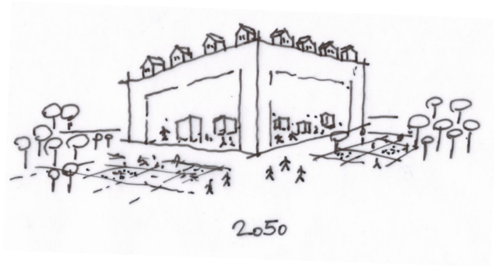
In 2050, the functional space of Luxembourg is fully transformed into a regenerative city-landscape. Formerly sprawled configurations have merged into the harmonious figure of an urban-natural archipelago consisting of a metabolic interplay of urban islands and productive landscapes. While green rings with organic farming, regenerative energy production, water and free spaces for leisure activities with a high quality of stay encircle the city islands, completely unplanned natural spaces and permaculturally designed open spaces for flora and fauna extend into the interspaces. The landscape is no longer a passive resource, but now plays an equivalent role to the city islands as a valuable public good. While the islands are given open borders to unbuilt areas, the biotopes running between these rings, such as forests, dry slopes, wetlands and meadows, are completely boundless. Depending on the climate morphology, they advance as cold air corridors into the urban cores and connect directly to built-up structures. These topologies of biodiversity can now be crossed undisturbed by animals and humans alike because they are no longer cut through by built infrastructures. From a bird's eye view, this urban landscape resembles a mycelia-like network of neuronal centres with a high degree of functional, energetic, ecological and food autonomy. They are distinctive in their own *Gestalt*, but interact with each other in a variety of ways. While these urban islands are connected by a free tramway network, which has been extended since 2020 and is now efficient and reliable, demand for individual transport on a regional and international scale is reduced, as many goods are produced locally and many activities are carried out regionally. It now exists in a reduced form of automated sharing formats, especially for residents of the villages from which the pressure to develop has been removed. But overall, mobility has decreased dramatically since the Corona crisis, when people realised that many trips, especially for business, were no longer necessary. The motorways between cities were eventually no longer needed and were abandoned at the end of the 2040s, since the rail network



provides mobility between cities. They are currently being partly converted into urban boulevards, partly used as energy production strips and partly re-naturalised at great expense to eliminate the fragmentation of the landscape.

The 15-Minute City

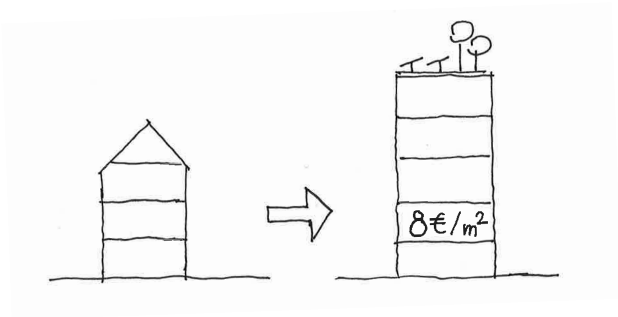
After the car had killed the city in the 20th century, according to André Gortz, it had killed itself in the 2020s and enabled a renaissance of the city. The new urbanity had already been in evidence very early on in car-free Dutch and Danish cities as well as in the superblocks in Barcelona, where initial experiments with the exclusion of the car from the city had shown that, contrary to what many had assumed, this had had quite positive effects on retail and the well-being of the inhabitants. It was made possible to overcome the horizontal functional separation of the car-friendly city through decentralisation and decoupling of working opportunities from the office buildings mainly located in the capital, the small-grained urban fabric and a resolute development of the tramway network within and between the urban islands. When the monocentric configuration of the functional space of Luxembourg reached its limits in the early 2020s, more and more companies, institutions and facilities decentralised from Luxembourg City. And because after the Corona pandemic of the early 2020s, employers no longer tied their employees to their facilities, it was possible, on the one hand, to combine living and working by consistently integrating co-working spaces in the hybrid urbanism and architecture and, on the other hand, to convert office space in central locations into affordable housing. This made the formerly homogenous cities socially more mixed and significantly livelier. And thus,



workers in jobs that cannot be performed through telework could eventually live closer to their workplace. Office workers' average commuting time dropped dramatically, with a co-working space in walking distance for most urban residents. At the same time, the many large structures on the Kirchberg plateau and in the Cloche d'Or were transformed into smaller structures, and the new districts were resolutely laid out in small-scale areas, thus intensifying the degree of mixing of living, working, producing, and education, shopping, entertainment, the range of social and health infrastructures and complementary urban uses in each city island. As soft mobility is now predominant, the urban landscape becomes "pedestrian friendly". Landscapes that were not at human scale, as in Kirchberg, have been transformed. The ground floors are converted into living spaces, the new buildings and the tree-filled landscape allow people to change their perception of space, which encourages urban life in public space. It can now be truly said that these are cities at a human scale, because people have reclaimed every possible square metre of the city from the car and the perimeter of the city islands is measured according to the so-called slipper distance, i.e. the distance that a resident is able to walk: a maximum of 500 to 750m from a public transport stop to his or her home, a maximum of 1 km to the necessary functions and social infrastructures, no more than 15 minutes of walking distance to the surrounding landscape.

Less than No Net Land Take

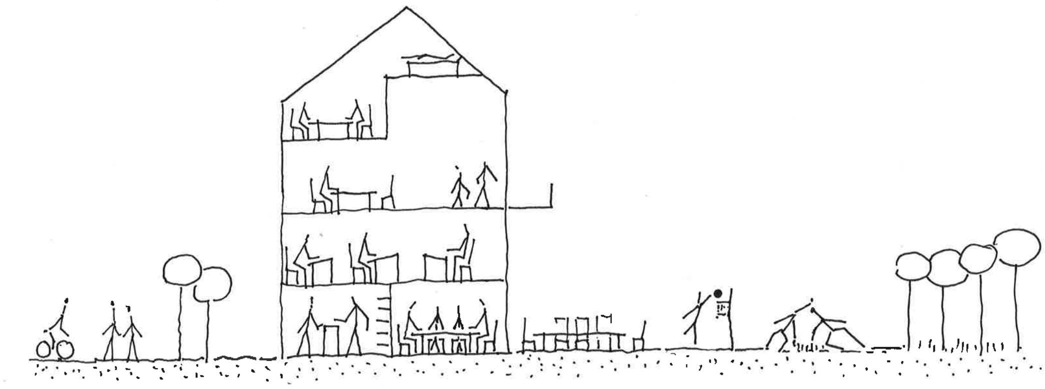
But how was it possible to create new housing and all the complementary uses for 400,000 new residents who had moved into the region, even though buildable plots had been declared open spaces to be devoted to other purposes than the construction of new buildings? The solution lied in using the already sealed surfaces of the fossil age. After the government initiated the turn in regional planning and stepwise released all brownfields, car parks, shopping malls, CO_2-intensive industrial estates, and motorways for transformation, the public sector had a substantial amount of land at its disposal. As a result, the goal of No Net Land Take was even surpassed, not only because all the plots of land ready for new constructions were re-naturalised, but also because many sealed surfaces of the



fossil age that were not needed for development were re-naturalised as well. This transformation process was started in the formerly monofunctional industrial and commercial zones. For example, when the Luxembourg-Esch tramway line, which was later to be extended further via Thionville to Metz, reached Foetz and Leudelange in the late 2020s, this was the opportunity to transform these previously dystopian places into lively urban neighbourhoods. Large shopping centres were overbuilt on the basis of the existing structure with appropriate housing typologies and were filled with market halls, co-working spaces, kindergartens and care facilities for the elderly. New small-scale buildings were erected in a radically diversified urban design on the parking areas that had previously been entirely empty in the evenings, on Sundays and public holidays. The same happened in many other monofunctional places such as the Cloche d'Or, Belval or on the Kirchberg plateau, on the Rue des Ardennes or in Mont-Saint-Martin. By making it possible to create all the necessary areas of use by transforming these already sealed surfaces, the pressure for development was also removed from rural areas, villages and farms.

Porosity

The urban islands are not compact, but are characterised by a high degree of porosity. This is because the buildable plots of land have not been developed since the middle of 2020 and, depending on their size, have been systematically transformed into multifunctional green spaces such as community gardens and city forests. The owners of the plots were given compensation in the new development areas where the buildings of the fossil-fuel era were overbuilt in multifunctional ways and equipped with either photovoltaic cells or green roofs, depending on roof pitch. The superstructure of existing buildings was given building permit, if another floor was transformed into social housing. In the course of the roof conversions, the underlying structures were also renovated in terms of energy efficiency. This made existing cities simultaneously more dense, porous and self-sufficient. The difference in temperature between urban and non-built up areas decreased noticeably. Thus, the cities in the region, which were particularly suffering from climate change effects like heat waves in the course of the 2020s, became considerably more resilient in facing the increasing weather extremes. For the new development areas, in which the remnants of the fossil fuel age are transformed, the focus has shifted to building cooperatives and co-housing buildings, following the formula that has proved successful in many European cities: "one third affordable housing, one third public or cooperative housing, one third privately financed housing." As more and more alternative housing models have been tested since the 2020s and mainstreamed in the 2030s, investor projects lost their attractiveness after housing shortages disappeared and the new models started to convince broader target groups with their multiple advantages. Private developers now also had to make an effort to meet the actual needs of the population. More and more citizens are now enjoying the opportunity to participate in the design of their housing projects far beyond just the interior design of their own flats. Benefiting from the introduction of ground leases and access to cheap land, users themselves now became commissioners. Since then, community buildings have increasingly invested in indoor and outdoor communal areas such as community kitchens, community gardens, guest flats and shared workshops, at the expense of individual areas, which have been significantly reduced from 53 m^2 in 2020 to 31+4 m^2 on average in 2050. But most residents experience this reduction as a liberation, as it was accompanied by a significant reduction of the number of under – or unused objects that formerly accumulated in individual flats, cellars and garages. And also the easy access to communal spaces reduced the burden and cost of building and maintaining such occasionally used spaces individually. In the course of the new communities, particular attention was paid in planning to the design of the thresholds between public and communal space on the one hand and the intimate spaces on the other. Everyone can now choose at any moment to be in company with others, but also in intimate space alone or with the family, with just a few steps between each. Since Luxembourg has traditionally had no experience with high densities, structurally dense quarters of the 2010s such as Belval and Cloche d'Or have by no means generated urbanity, and finally the mainstream discourse of densification became obsolete at a stroke during the Corona crisis, new developments will revolve around a FAR of 1 to a maximum of 1.5. The ground floors facing the street are filled with shops, workshops, cafés or restaurants, often with hybrid forms of these different functions. Towards the community gardens are the common rooms and co-working spaces, which are organised thematically but in an interdisciplinary way and often also occupy the upper floors. They are used at all times of the day and all days of the week for different purposes, work, education, leisure, self-governance and civic engagement. Above them are the flats of various sizes and typologies, which allow for different forms of community and privacy and bring the generations together. In this



way, functional and social heterogeneity extends from the scale of the urban islands through the neighbourhood to the granularity of the buildings. Hybrid ownership and multiple functions of these buildings necessitate flexible building configurations, including so-called “third spaces” at the interface of public, civil society and commercial uses.

Triple zero in the building sector: zero CO_2, zero fossil energy, zero waste

During the 2020s, the Triple-Zero-Principle for buildings became state of the art: zero CO_2, zero fossil energy, zero waste. New regulations in the early 2030s made this the new mandatory standard. They boosted circular economy innovations in the building sector, which, among other things, re-established regional wood as carbon capturing structural building material and generalised wood building techniques for multi-story buildings, but also regionally produced self-building kits. Here, like in other economic sectors, a shift in the taxation system away from taxing employment and instead increasing the taxation of resource use became an important trigger for changes in product design, maintenance and reuse services, creating a range of new occupational opportunities all along the value chain that are bound to the region and that hence cannot be delocalised.
In the new era of the regenerative city-landscape, buildings are constructed in a neutral but spacious structure using a few natural, mostly regionally produced materials that are fully reusable and recyclable. The generous structure made them versatile in terms of their uses and allows them to be easily adapted to changes in the needs and constellations of families, co-housing or co-working communities. Typologically they are very diverse: from urban villas, open block perimeter developments, carpet houses and terrace houses. In the 2030s a trend unfolded to create modular kits – similar to James Wines’ Highrise of Homes – that can be used across building types, thus reducing building costs for the first time again after decades of increasing costs per square meter.

Regional Sharing Economy

The 2050 economy is mainly structured along regional value chains and operates according to principles of the common good. In respect of subsidiarity, economic cooperation within the region is pursued wherever possible and with other regions of Europe and the world wherever necessary. The financial sector transformed from a driving force of the former growth regime to a globally leading hub of innovations for financing large-scale socio-ecological transitions, with the Luxembourg functional region as its test-bed. All options have been improved in the 2020s and mainstreamed in the 2030s: besides alternative currencies, microfinance and crowdfunding, also social or citizen banking, cooperative lending and impact bonds. The remaining speculative variants of "financialised finance" prone to bubbles and bursts have been banned in the 2040s, reconnecting finance to the "real economy" and to the societal needs across sectors to make leaps in decabornisation of the sustainability transition. New standards in product design (longevity and repairability) and use (e.g. Sustainable Product Service Systems – SPSS) reduced demand for new products and increased demand in maintenance and repair services. This includes (partly community-based) sharing schemes, the empowerment of users through public repair facilities (e.g. maker spaces, fab-labs, repair cafés) and related education and training offers. Consumption was also reduced after work time models became radically diversified and flexible at the beginning of the 2030s and a new ratio between paid labour and hitherto unpaid work became widespread, distributing available time more evenly between work in the global economy, work in the regional economy, work in the community (subsistence, civic engagement) and work on oneself (sufficiency-oriented lifestyle). Less hours spent on paid work every week and less hours lost in commuting means more time available for other activities. This increased life satisfaction and it would have also increased decarbonisation rebound effects, if people had not also earned less money as a consequence of paid work time reduction. This, in turn, has been much debated and criticized by people used to economic growth and associated regular salary rises. But in fact, less disposable income did not decrease life satisfaction, because in a regional sharing economy with individual and collective sufficiency strategies, there is also less need for money (because of more sharing, caring, repairing, and own production), and through the 15-minute city the mobility needs are reduced).

Food Sovereignty

The food chain from seeds to compost is organised in a circular way, and a more diversified set of crops are grown in Luxembourg, such that the food system has become more resilient. The overarching principle of this endeavour is food sovereignty, i.e.

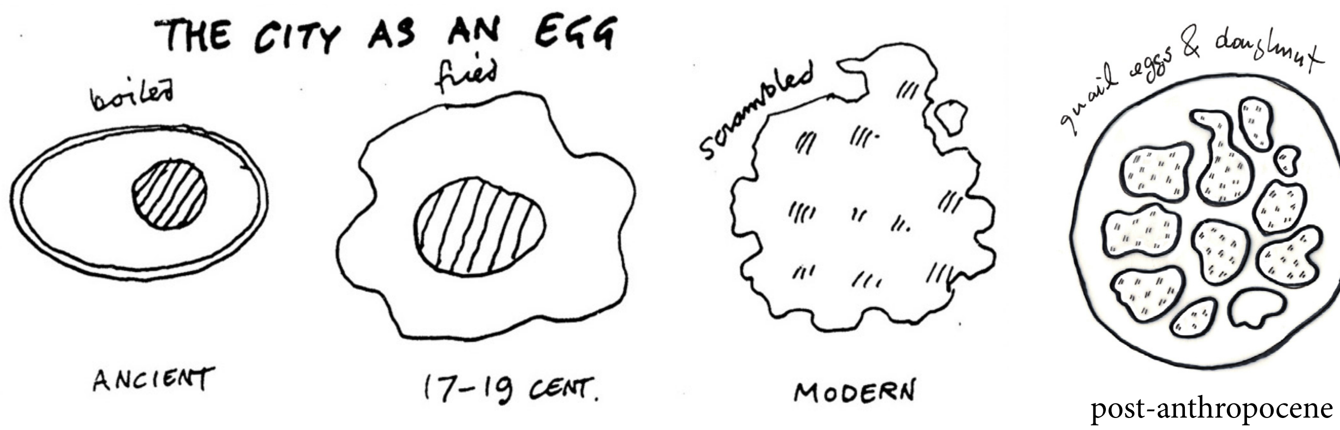
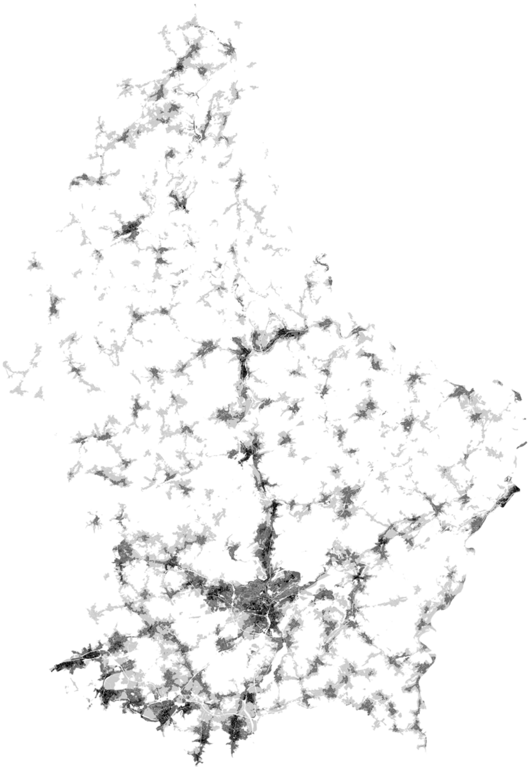


Figure 31. An extension of Cedric Price's diagram of the city as an egg.

maximising the diversity and availability of locally produced food in a democratic way, ensuring equity and participation of producers and citizens. Community supported forms of agriculture became more and more widespread in the past 25 years, provided income security for farmers and led to changes in ownership, decision making and production strategies. These structural changes were complemented by new forms of urban farming. "*Wandergärtner*innen*" (itinerant gardeners) with their citizen-oriented advisory activities characterise a new horticulture, which has spread out over small areas in a mosaic-like manner in the urban and peri-urban landscape. Land-use patterns changed in rural and peri-urban areas, but also within urban contexts. The partial agricultural use of public green spaces as well as the set-up of private lots and buildings (e.g. roof gardens) for small scale farming activities required changes in urban and building design and in building regulations and zoning bylaws, which became fully conducive for these new uses of green space from 2030. Livestock is reduced to ensure a varied, yet mainly plant-based diet while keeping animal products as high-quality components albeit in reduced quantity, for a more conscious consumption. There is also a communal composting plant in each neighbourhood, and a cooperative biogas plant at a larger regional scale. Most importantly, several initiatives have reduced food waste by 80%, such as new markets for imperfect produce, just-in-time food shopping at stores within walking distance to reduce food waste at home, and infrastructure for food donations to the social and solidarity sector. There is one Food Council per rural-urban region as a tried and tested tool of a true food democracy, consisting of all actors in the chain. Regional "houses of food" hold popular food events and train people in new professions in the food system, and also serve as a place where food is produced and cooked on a cooperative basis.

Transition Governance

In the course of the 2020s, an increasing number of cities created TUBs (transition hubs) to activate the collective intelligence of their residents and of organisations of all sectors connected to their place to find out together through which measures and projects to meet the yearly carbon emission reduction targets the PDZC (plan directeur zéro carbone) requested from them. Each TUB of the functional region can call on targeted support from experts connected in cross-border system innovation networks that have been established for each transition focus domain (energy, food, building, mobility etc.). Once system innovation networks had also been created for cross-cutting challenges like regional value chains, transition governance and transition learning, capacity building for system redesign reached a critical threshold in 2035 for transition programmes and projects to become self-accelerating and self-disseminating across the entire region, and beyond. As a result, today it appears inconceivable that not all people, groups and organisations which are around in the functional region participate and co-determine the further development of their interconnected urban islands and rural landscapes, regardless of their voting rights in national politics. Consciousness researchers had advised politicians not only to make courageous yet fair decisions, but to take people along in a way that truly celebrated change (e.g. by celebrating every liberated car park as a reclaiming of the habitat outside the door). Substantial investment went to blended learning for the transition, combining the best of online sharing of top-notch international knowledge on system innovations and systemic interventions and hands-on immersive learning in local transition initiatives and transition hubs, in new co-creative and intergenerational ways. This new mode of individual and social learning for local and regional transitions became so important over the years that the formal education system increasingly adopted it. This is how Peter Sloterdijk's 2020 demand became true towards 2050: The society became indeed initiated to a large seminar into harmless life.



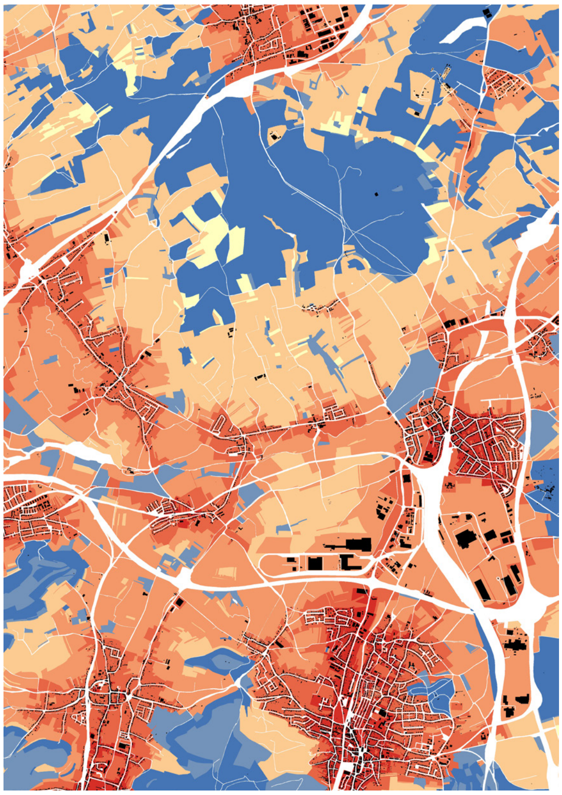


Figure 32. The map shows the suitability of parcels in Luxembourg for further densification. It offers an example of the Multi Criteria Evaluation Analysis methodology, and is a result of research for the Ecocentury project, funded by the Braillard foundation. In this case, the suitability envelope is calculated taking into consideration geospatial layers that favor the development of compact cities, such as distance from existing building and infrastructure density, landscape fragmentation, walking accessibility to selected functions. The darker the grayscale gradient, the higher the degree of suitability.

Figure 33. The map shows a more detailed version of the research case on densification suitability from the Ecocentury project. In this case, the color scale highlights in gradient of red the most suitable areas, and in gradient of blue the least suitable areas for development.

03 Next Steps: Intentions for the Second and Third Stage

Stage 2: Spatialization and simulation

In the second stage of the consultation, we will spatialise the decarbonisation path and the interventions for resilience presented in this report in the specific functional space of Luxembourg. Our proposed changes to agriculture, forest area, and housing directly affect land use, while our changes to mobility have profound effects on the regional transportation network.

Green belts

We will investigate where and to what extent the green belts will be best placed next to existing urban settlements, and upon which structure these belts will be programmatically created. This process will heavily rely upon a geo-design methodology, which will proceed through multicriteria evaluation analysis (MEA) of selected geospatial variables to define which areas are the most suitable for hosting those belts. The criteria for defining this Suitability Index for the green belts, will include geospatial variables mostly connected to ecological processes, such as the quality of the soils, topographical features, and the structure of existing vegetation and elements of natural geography (such as hydrological systems).
This process of geospatial modelling will help identify where farmland, forests, recreational areas, sports facilities, etc. should most suitably be located and what dimensions they should take. Based on this geospatial background, the natural belts will be further formalized through design investigations.

Figure 34. Many cities like Barcelona, Paris or Hamburg start to transform former highways and main traffic roads into urban boulevards. In Hamburg, a *Planungswerkstatt* about this transformation with more than 200 experts and 8000 visitors/participants took place in 2019.

Densification of existing settlements

The same methodology will be also followed for specifying the spatial pattern of the densification of existing settlements. In this case, the multicriteria evaluation analysis will explore opportunities for densification across the existing built fabric, by classifying it according to its suitability to accommodate further density. A first set of explorations will model geospatial information of existing car parks, and other car-oriented facilities, as well as large scale monofunctional commercial areas in existing settlements. A second investigation will map the potential of existing roofscapes to accommodate either the development of superstructures (and thus additional built volume), or the construction of green roofs, or in the case of pitched roofs, the installation of photovoltaic panels. The respective share of measures will of course depend on the metrical gains in terms of decarbonisation. An additional set of explorations will use the methodology of multicriteria evaluation analysis in order to explore the accessibility of the territory of Luxembourg, according to walking and biking distance to selected social infrastructures, as well as public transport stops (bus, tramway, and train stops). This exploration will be crucial for relating the possibility for densification, with the accessibility of these new areas of density to existing and proposed necessary functions, according to the principle of the 15-minute city, thus avoiding the past failures of creating large areas of affordable housing with low degrees of accessibility and connectivity to amenities and central functions. Finally, another geospatial investigation will classify land that is ready for construction according to two dimensional sizes: land that will be transformed into community gardens and open spaces and (much larger) land areas where urban forests can be created. Climatic morphologies will also be mapped, which will reveal where cold air corridors and urban forests will have to be created.

Figure 35. Co-design planning meeting for the Piazza Verde urban gardening project at creative space 1535°C in Differdange in 2015. This project catalysed interaction between the users of the 1535°C space, and neighbours from the surroundings as well as food activists. The project was conducted by TransitionMinett/CELL and Socialmatter.

New urban islands

In a similar way, the methodology of multicriteria evaluation analysis will also be used for the definition of the areas of creation of the new urban islands on the land of the fossil age: The geospatial layers will bring together commercial areas, brownfields and car-oriented structures and infrastructures outside existing settlements. It will be necessary to examine the extent and where exactly it makes sense to create new neighbourhoods in these areas, how they can be connected to the tramway and train network, and which urban and architectural structures and which hybrid urbanistic programmes can be created that closely combine living, working, producing, leisure, etc. in different granularities. It will be a matter of developing new typologies of land use, neighbourhoods and buildings, so that the 15-minute concept will be realized here, in the new developments, as well.

Population growth: Phasing map of development

In anticipation of about 400,000 new inhabitants, a phasing map will be created where these developments should proceed in stages of decades: first on brownfields and commercial centres, in a second step on car parks and petrol stations, finally possibly also partly on motorways, etc., so that the balance will be below the No Net Land Take in each decade. The result of this development will be represented in maps, plans, physical and virtual models. Each spatialisation and conceptualisation will be assessed for the achievability of the goals (decarbonisation and resilience) through our metrics presented in this first report, i.e. this design process will be accompanied by continuous monitoring. We will elaborate also more on the role that coordination and complementarities across the Greater Region can play in ensuring a more rapid decarbonization.

Mobility: Regional transportation network

Our decarbonisation path relies on substantial changes to mobility: overall reduction in commuting, reduction in air travel, switch to smaller and electric vehicles, reduction in individual car ownership, and an increase in car sharing as well as local and regional public transportation via buses and trains. This reduction in travel as well as the change in the mode of transportation will be spatialised in Stage 2 by extending the modelling completed for the project HERMES at LIST. This project was based on a close collaboration between ENGIE and LIST, and produced a decision-making tool for territories to assess the medium-term consequences of mobility policies. LIST combined life-cycle assessment methods with agent-based modelling and developed scenarios to identify the most efficient policy levers to trigger a sustainable mobility based on real-world data. The project included both captive fleets (e.g. taxis, company cars, urban freight distribution) and private vehicles, for which environmental impacts, public acceptance and decision criteria were simulated over a twelve-year period. Spatialisation of the mobility interventions is a complex but crucial exercise, given the need for coordination across the Greater Region and their outsize influence on GHG emissions.

Refining the impact assessments of the decarbonisation and resilience interventions

In this proposal, we presented detailed life-cycle impact assessments across multiple indicators for combined measures in the mobility, housing, and agriculture domains. For other measures we estimated the impact only on GHG emissions. In Stage 2, we will complete the life-cycle impact assessments for the remaining interventions and the remaining indicators. This will allow us to construct a more detailed decarbonisation path, alongside potential co-benefits or trade-offs on other areas of environmental and social impacts (air pollution, excess nutrient emissions, material requirements, wellbeing). In addition, we will refine the timing of each intervention to produce a more realistic decarbonisation timeline. With more calculated interventions at our disposal, we can then construct different decarbonisation scenarios that could be evaluated by residents and cross-border commuters.

Transition clusters and workshops

Complementary to and iteratively with mapping and assessing the most promising spatial transition potentials, we will also map and assess relevant social transition potentials in terms of clusters of sustainability-oriented initiatives, projects and programmes across sectors (public, private, civil society, research & education). The methodological steps will be:

a) operationalisation of criteria for transformative capacity based on relevant literature (Mader 2013; Strasser, de Kraker & Kemp, 2019; Wolfram 2016).

b) identification of activity clusters that are pertinent for the zero-carbon transition by exploring and crossing various available sources of data (e.g. database of Aktioun Nohaltegkeet ; INTERREG, LIFE and LEADER projects, climate pact, platform of transition initiatives, domain-specific platforms,

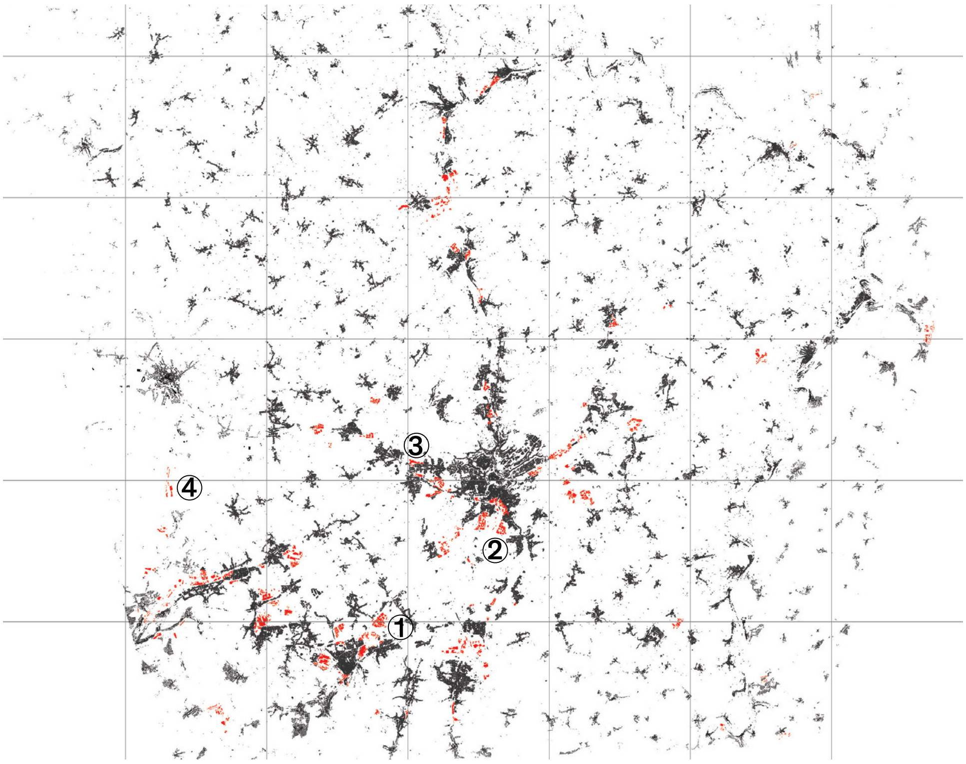


Figure 36. Potential sites on land of the fossil age.

research projects, in particular those with action research and living lab approach).

c) criteria-based selection of ca. 10 “transition hotspots” at different scales, neighbourhood, city and (cross-border) region.

d) focus groups with transition pioneers from the selected hotspots on opportunities and barriers for collaboration, joint innovation and scaling (Lam et al. 2020).

e) a ‘Resilience-check workshop’ (together with the Sustainability Science team at UL) in which our vision for Luxembourg will be juxtaposed to the three NEXUS FUTURES Scenarios in order to identify which aspects of the vision may need to be strengthened or complemented in order to make the vision more ‘future-robust’ vis à vis other possible futures and development paths and disruptive events. Focus group discussion will elicit consumer preferences and identify those interventions that are likely to meet the most resistance.

f) short, template-based documentation of the findings and integration in the geographical maps.

g) crossing the spatial and social transition potentials to determine the selection of sites for stage 3.
Stage 3: Projection and Experimentation

In the third phase, the approaches will be conceptualised in emblematic sites. Those sites will be chosen for an intervention according to the following typology:

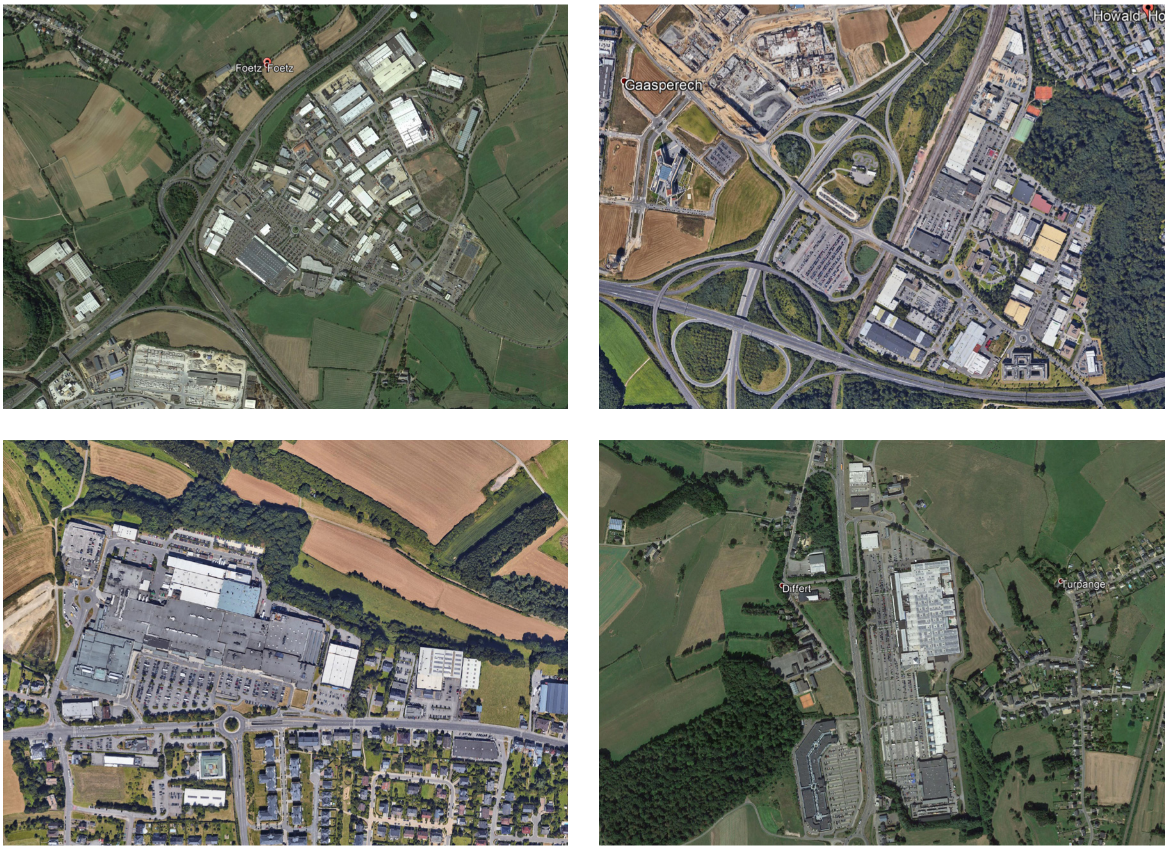


Figure 37. Fossil Age Infrastructure and potential sites
1. Foetz
2. Howald/Gasperich
3. Route d'Arlon
4. Messancy

a) an existing medium-sized city (Luxembourg City, Trier, Metz) and a smaller existing city (Longwy, Arlon, Differdange, Esch, Ettelbrück, Merzig...), to show how the 15-minutes-principle, porosity, green belts can be concretely designed and implemented in existing cities.
b) a brownfield (Differdange, Dommeldange or Esch...)
c) an industrial zone (Leudelange, Sandweiler-Contern...)
d) a commercial zone (Foetz, Howald, Mont Saint Martin...)
e) a relatively new district composed of big monofunctional structures (Kirchberg, Cloche d’Or. . .), and/or a linear shopping or refuelling strip (Route d'Arlon, Rue des Ardennes, Wasserbillig-Mertert...), to show how these sites can be regenerated and transformed into diversified and sustainable urban neighbourhoods according to our principles without sealing more land.

Models will also be developed for these sites on how to:
a) legally treat the land (ground leases and the like)
b) organise housing production (cooperatives, co-housing, innovative social housing)
c) design the buildings programmatically, structurally and materially
d) develop appropriate transportation infrastructure
e) involve individual citizens and organised stakeholders in urban development decisions in a fair and transparent way
f) achieve collective sufficiency behaviour (social learning, self-responsibility, technology...).
g) make this transition to new life worlds and lifestyle rewarding and enjoyable
h) make the shape of the 2050 landscapes, cities and neighbourhoods aesthetically exciting.

04 Outlook

This exercise is important, because substantial ignorance or misinformation exists on the relative contribution of our consumption activities as well as mitigation measures to GHG emissions. Misconceptions exist at the individual level as well as at the societal or government level. Without the holistic exercise that we are undertaking at the behest of LiT, these types of comparisons on activities and measures would not be instituted. Misapplication of effort and inefficiency is the result.

Avoided GHG emissions for selected activities :

- turn off devices instead of standby: -25 kg CO_2 eq./year
- turn off lights: -1 kg CO_2 eq./year
- empty your inbox: -20 kg CO_2 eq./year for 1000 emails
- stop eating meat: -1000 kg CO_2 eq./year
- refrain from flying: -1200 kg CO_2 eq./year

Our ability as individuals and as a society to change our lifestyles as substantially as required to meet the Paris 2°C scenario hinges first and foremost on a correct and complete accounting of how our consumption in Luxembourg contributes to climate change while avoiding increasing other social and environmental impacts. While information on the GHG impacts of different activities is broadly available, it is often not specific to Luxembourg, nor collected systematically across different types of activities to make comparisons possible, nor collected alongside other environmental or social impacts that identify trade-offs and co-benefits. Armed with this knowledge, individuals and regulators can become informed actors and drive the decarbonisation transition.

The enormity of the required change in lifestyles and infrastructures means that a mere quantification of a change in activity, such as a reduction in the per capita living space from 53 to 31 m^2 plus 4 m^2 of shared space to reduce energy use in heating, is not sufficient for the creation of a vision for Luxembourg in 2050. These changes need to be spatialised and distributed over time in order to create a concrete plan to shape development in Luxembourg. Defining and visualising a resilient decarbonisation timeline thus requires the complementary activities of quantification and design. Our analysis shows that decarbonisation by 2050 is possible and that the landscape and cityscape of 2050 would be an attractive place to live.

ANNEX


Nach Hause kommen
Mit Nachbarschaften der Klimakrise begegnen
Nach Hause kommen
Nachbarschaften als Commons
Befreiung vom Überfluss
NIKO PAECH
AUF DEM WEG IN DIE POSTWACHSTUMSÖKONOMIE
oekom
ASSOCIATION NÉGAWATT
CHANGEONS D'ÉNERGIES
TRANSITION, MODE D'EMPLOI
P.M.
Neustart Schweiz
So geht es weiter
KEN ROBINSON
OUT of OUR MINDS
Learning to be Creative
NEW EDITION, FULLY UPDATED
PERMACULTURE
A Designers' Manual
BILL MOLLISON
CYRIL DION
PETIT MANUEL DE RÉSISTANCE CONTEMPORAINE
PIERRE RABHI
VERS LA SOBRIÉTÉ HEUREUSE
ACTES SUD
POST CARBON READER
POSTWACHSTUMS-GEOGRAPHIEN
Raumbezüge diverser und alternativer Ökonomien
Postwachstumspolitiken
Wege zur wachstumsunabhängigen Gesellschaft
POURQUOI LES FEMMES VONT SAUVER LA PLANÈTE
LE MANIFESTE ÉCO-FÉMINISTE
Préface de ANNE HIDALGO
RETROSUBURBIA
THE DOWNSHIFTER'S GUIDE TO A RESILIENT FUTURE
DAVID HOLMGREN
THE GREEN NEW DEAL
WHY THE FOSSIL FUEL CIVILIZATION WILL COLLAPSE BY 2028, and THE BOLD ECONOMIC PLAN TO SAVE LIFE ON EARTH
JEREMY RIFKIN
ROB HOPKINS
FROM WHAT IS TO WHAT IF
UNLEASHING THE POWER OF IMAGINATION TO CREATE THE FUTURE WE WANT
Sacred Economics
Charles Eisenstein
SORTONS DE L'ÂGE DES FOSSILES !
Maxime Combes
UWE SCHNEIDEWIND
ANGELIKA ZAHRNT
The Politics of Sufficiency
MAKING IT EASIER TO LIVE THE GOOD LIFE
DAVID BOSSHART
THE AGE OF LESS
DIE NEUE WOHLSTANDSFORMEL DER WESTLICHEN WELT
Ali Cheshmehzangi
The City in Need
Urban Resilience and City Management in Disruptive Disease Outbreak Events
Springer
THE SUNDAY TIMES BESTSELLER
THE FUTURE WE CHOOSE
Christiana Figueres
Tom Rivett-Carnac
Surviving the Climate Crisis
TOBY HEMENWAY
THE PERMACULTURE CITY
Regenerative Design for Urban, Suburban, and Town Resilience
THINK LIKE A COMMONER
A Short Introduction to the Life of the Commons
DAVID BOLLIER
NAOMI KLEIN
THIS CHANGES EVERYTHING
CAPITALISM vs THE CLIMATE
TIM JACKSON
WOHLSTAND OHNE WACHSTUM
BERND SOMMER
HARALD WELZER
TRANSFORMATIONSDESIGN
Wege in eine zukunftsfähige Moderne
THE TRANSITION COMPANION
Making your community more resilient in uncertain times
Rob Hopkins
PABLO SERVIGNE
RAPHAËL STEVENS
GAUTHIER CHAPELLE
UNE AUTRE FIN DU MONDE EST POSSIBLE
Vivre l'effondrement (et pas seulement y survivre)
Par les auteurs de COMMENT TOUT PEUT S'EFFONDRER
URBAN Permaculture
A Practical Handbook for Sustainable Living
David Watkins
URBAN PIONEERS
THE INTERNATIONAL BESTSELLER
UTOPIA FOR REALISTS
AND HOW WE CAN GET THERE
RUTGER BREGMAN
Ernst Ulrich von Weizsäcker
Anders Wijkman u.a.
Club of Rome: Der große Bericht
WIR SIND DRAN
Was wir ändern müssen, wenn wir bleiben wollen
Eine neue Aufklärung für eine volle Welt
FUTURE SCENARIOS
How Communities Can Adapt to Peak Oil and Climate Change
DAVID HOLMGREN
Hartmut Rosa
Resonanz
Eine Soziologie der Weltbeziehung
suhrkamp taschenbuch wissenschaft
BRUNO LATOUR
FACING GAIA
EIGHT LECTURES ON THE NEW CLIMATIC REGIME


The Ecological Transition
Cultural Anthropology and Human Adaptation
With a new preface by the author
John W. Bennett
Steps to an Ecology of Mind
Gregory Bateson
Ernest Callenbach
Ökotopia
Fischer Bücherei
Bücher des Wissens
Vance Packard
Die grosse Verschwendung
Kate Raworth
Die Donut-Ökonomie
Endlich ein Wirtschaftsmodell, das den Planeten nicht zerstört
Hanser
Ernst Friedrich Schumacher
Small is beautiful
Die Rückkehr zum menschlichen Maß
oekom
Yuval Noah Harari
21 Lessons for the 21st Century
Eine globale Prognose für die nächsten 40 Jahre
2052
Jørgen Randers
Der neue Bericht an den Club of Rome
oekom
Harald Welzer
Eine Gesellschaftsutopie für freie Menschen
Alles könnte anders sein
Fischer
Architektur auf gemeinsamem Boden
Positionen und Modelle zur Bodenfrage
Lars Müller Publishers / Universität Luxemburg
Befreiung vom Überfluss
Niko Paech
Auf dem Weg in die Postwachstumsökonomie
oekom
P.M.
bolo'bolo
Climate
A New Story
Charles Eisenstein
Comment tout peut s'effondrer
Pablo Servigne
Raphaël Stevens
Seuil
Silke Helfrich und Heinrich-Böll-Stiftung (Hg.)
Commons
Für eine neue Politik jenseits von Markt und Staat
[transcript]
Silke Helfrich, David Bollier und Heinrich-Böll-Stiftung (Hg.)
Die Welt der Commons
Muster gemeinsamen Handelns
[transcript]
Matthias Horx
Das Buch des Wandels
Wie Menschen Zukunft gestalten
DVA
Designing Regenerative Cultures
Daniel Christian Wahl
donella h. meadows
die grenzen des denkens
wie wir sie mit system erkennen und überwinden können
oekom
Die Kunst des Wandels
Ansätze für die ökosoziale Transformation
oekom
The Sunday Times Bestseller
Doughnut Economics
Seven Ways to Think Like a 21st-Century Economist
Kate Raworth
New York Times Bestseller
Drawdown
The Most Comprehensive Plan Ever Proposed to Reverse Global Warming
Edited by Paul Hawken
Claude Turmes
Die Energiewende
Eine Chance für Europa
oekom
L'effondrement de l'empire humain
Regards croisés
Pablo Servigne
Gauthier Chapelle
L'entraide
L'autre loi de la jungle
Mike Berners-Lee
Es gibt keinen Planet B
Das Handbuch für die Herausforderungen unserer Zeit
Christian Felber
Gemeinwohl-Ökonomie
Piper
Valentin Thurn
Gundula Oertel
Christine Pohl
Genial lokal
So kommt die Ernährungswende in Bewegung
oekom
The Sunday Times Bestseller
Humankind
A Hopeful History
Rutger Bregman
Integrale Ökologie
Sean Esbjörn-Hargens
Michael E. Zimmerman
Just share it!
On Fire
The Burning Case for a Green New Deal
Naomi Klein
Claas Triebel
Tobias Hürter
orell füssli
Die Kunst des kooperativen Handelns
Eine Agenda für die Welt von morgen
L'âge des low tech
Philippe Bihouix
Seuil
Le Luxembourg en 2050
De l'aménagement au ménagement du territoire
Covid-19
Pascale Junker
Möglichkeitsräume
Raumplanung im Zeichen des Postwachstums
oekom

Bibliography

Affolderbach, J., & Carr, C. (2016). Blending scales of governance: Land-use policies and practices in the small state of Luxembourg. In: Regional studies, 50(6), pp. 944-955.

Aktioun nohaltegkeet (2020). Aktioun-Nohaltegkeet. [online] Available at: <https://www.aktioun-nohaltegkeet.lu> [Accessed 15 December 2020].

Alewell, C. et al. (2020). Global phosphorus shortage will be aggravated by soil erosion. In: Nature communications, 11(1), pp.1-12.

Ali S. et al (2020). Resource Efficiency and Climate Change. Material Efficiency Stategies for a Low-Carbon Future. UN environment programme. International Resource Panel. Nairobi. [online] https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change [Accessed 18 December 2020].

AMO/Koolhaas (2020). Countryside, A report. Cologne: Taschen.

Arbault, D. (2014). Integrated earth system dynamic modeling for Life Cycle Impact Assessment of Ecosystem Services. Science of the Total Environment, 472, pp. 262-272.

Atoz (2019). Les attitudes et l'implication de la population Luxembourgeoise à l'égard des défis écologiques et climatiques. Atoz Tax Advisers Luxembourg. [online] http://download.rtl.lu/2019/09/19/76750e3cad8bc0968398a268590cc835.pdf [Accessed 6 December 2020].

Audsley, E. et al. (2009). Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. Cranfield University. DOI: 10.13140/RG.2.1.5095.3122

Balaban, O. & Puppim de Oliveira, J. A. (2013). Urban Regeneration and Climate-friendly Development: Lessons from Japan. https://unu.edu/publications/articles/urban-regeneration-and-climate-friendly-development-lessons-from-japan.html.

Bannon, E. (2020). Plug-in hybrids: Is Europe heading for a new Dieselgate? [online] https://www.transportenvironment.org/publications/plug-hybrids-europe-heading-new-dieselgate [Accessed 18 December 2020]

Barnett, C. (2015). Towards a Geography of Injustice. In: Epifyytti, pp. 111-118.

Barnett, C. (2017). The Priority of Injustice: Locating Democracy in Critical Theory. Athens, GA: University of Georgia Press.

Bauler, T. (2020). We should continue this dialogue with the EU institutions. In: Lange, B. et al. (eds.) Postwachstumsgeographien. Bielefeld: Transcript, pp. 321-326.

Becker, T., Hesse, M. & Schulz, C. (2019). Qualitatives Wachstum in Stadt und Land? Elefant im Raum und zugleich leerer Signifikant. In: Reckinger, C. & Urbé, R. (eds.): Sozialalmanach 2019. Schwéierpunkt: Qualitativen Wuesstem. Luxemburg: Caritas, pp. 273-288.

Becker, T. & Hesse, M. (2020). A Temporary Space Where Development And Planning Emergencies Meet? Notes On An International Building Exhibition (IBA) In The Cross-Border Territories Of France And Luxembourg. [online] Taylor & Francis. Available at: <https://www.tandfonline.com/doi/full/10.1080/14649357.2020.1842588> [Accessed 14 December 2020].

Brokow-Loga, A. & Eckardt, F. (2020). Postwachstumsstadt. Konturen einer solidarischen Stadtpolitik. Munich: oekom.

Brown, M. (2016). FutuREstorative: Working Towards a New Sustainability, 1 edition. London: RIBA Publishing.

Burckhardt, L. (1981). Selberbauen, ökologisch bauen, regional bauen. In: Andritzky, M., Burkhardt, L., Hoffmann, O. (eds.), Für eine andere Architektur. Bauen mit der Natur und in der Region, Frankfurt a. M: Fischer Verlag, pp. 9-13.

Burke, M. et al. Ländliche Verheissung. Arbeits- und Lebensprojekte rund um Berlin. Berlin: Ruby-Press.

Caruso, G. et al. (2020). Editorial: Challenges, Specificities And Commonalities Of Transport Research And Policy Within The Benelux Countries – The Case Of Luxembourg. [online] Journals.open.tudelft.nl. Available at: <https://journals.open.tudelft.nl/index.php/ejtir/article/view/3094> [Accessed 14 December 2020].

Cobb, C., Halstead, T., Rowe, J. (1995). The Genuine Progress Indicator: Summary of Data and Methodology. San Francisco: Redefining Progress.

Country Overshoot Day (2020). [online] Available at: <https://www.overshootday.org/newsroom/country-overshoot-days/> [Accessed 14 December 2020].

Creos (2018). Scenario Report 2040 "Network Development Plan 2040 Electrical Energy Grid", Creos, Version 1.0. [online] https://www.readkong.com/page/scenario-report-2040-7655831. [Accessed 15 December 2020].

Creos (2020). Actualités – Creos Luxembourg S.A. – Gestionnaire De Réseaux D'Électricité Et De Conduites De Gaz Naturel. [online] Available at: <https://www.creos-net.lu/actualites/actualites/article/scenario-report-2040-public-consultation.html> [Accessed 15 December 2020].

Daly, H.E., Cobb, J.B. (1989). For the Common Good: Redirecting the Economy. Toward Community, the Environment, and a Sustainable Future; Boston: Beacon Press.

Daly, M. (2017). Quantifying the environmental impact of ecovillages and co-housing communities: A systematic literature review. In: Local Environment, 22(11), 1358–1377. [online] https://doi.org/10.1080/13549839.2017.1348342.

Davoudi, S. & Brooks, E. (2014). When does unequal become unfair? Judging claims of environmental injustice. In: Environment and Planning A 2014, volume 46, pp. 2686-2702.

de Blas, I. et al. (2020). The limits of transport decarbonization under the current growth paradigm. In: Energy Strategy Reviews, 32, 100543.

De Brabanter et al. (2020). Fourth Biennial Report of Luxembourg under the United Nations Framework Convention on Climate Change. Ministère de l'Environnement, du Climat et du Développement durable. [online] Available at: <https://unfccc.int/sites/default/files/resource/BR4_LUX_Final_201123.pdf> [Accessed 15 December 2020].

DGE (2020). Ernährungskreis. [online] Available at: <https://www.dge.de/ernaehrungspraxis/vollwertige-ernaehrung/ernaehrungskreis/> [Accessed 15 December 2020].

De Flander, K., & Brugmann, J. (2017). Pressure-point strategy: Leverages for urban systemic transformation. In: Sustainability, 9(1), p. 99. [online] https://doi.org/10.3390/su9010099.

Demaria, F., Kallis, G., Bakker, K. (2019). Geographies of degrowth: Nowtopias, resurgences and the decolonization of imaginaries and places. In: Environment and Planning E:Nature and Space, 2(3), pp. 431-450. doi: 10.1177/2514848619869689.

De Ponti, T., Rijk, B., Van Ittersum, M.K. (2012). The crop yield gap between organic and conventional agriculture. In: Agricultural systems, 108, pp. 1-9.

Desreveaux, A. et al. (2020). Techno-Economic Comparison of Total Cost of Ownership of Electric and Diesel Vehicles. In: IEEE Access, 8, 195752-195762.

Doick, K. J., Peace, A., Hutchings, T. R. (2014). The role of one large greenspace in mitigating London's nocturnal urban heat island. In: Sci Total Environ, 493: pp. 662-71.

Durand, F. et al., (2018). Schéma de Développement Territorial de la Grande Région. Cahier thématique n° 3. Développement économique. INTERREG. [online] Available at: <https://amenagement-territoire.public.lu/content/dam/amenagement_territoire/fr/affaires_transfrontali%C3%A8res/Cahier-Thematique-n-3-FR-final.pdf> [Accessed 14 December 2020].

EC (2011). European Commission's White Paper on Transport. Roadmap to a single European Transport area – towards a competitive and resource-efficient transport. Luxembourg: European Union 2011. [online] Available at: <https://ec.europa.eu/transport/themes/strategies/2011_white_paper_en> [Accessed 15 December 2020].

EC (2020) Standard values for emission factors https://ec.europa.eu/energy/sites/ener/files/documents/Standard%20values%20v.1.0.xlsx

Eckelman, M.J. & Sherman, J. (2016). Environmental impacts of the US healthcare system and effects on public health. In: PloS one, 11(6), p.e 0157014.

Ecolise (2020). Home – Ecolise / European Network For Community-Led Initiatives on Climate Change and Sustainability. [online] Available at: <https://www.ecolise.eu/> [Accessed 15 December 2020].

Elgar, F.J., Stefaniak, A., Wohl, M.J., (2020). The trouble with trust: Time-series analysis of social capital, income inequality, and COVID-19 deaths in 84 countries. In: Social Science & Medicine, 263, 113365.

Eng Aerd (2020). Engaerd. [online] Available at: <https://www.engaerd.lu> [Accessed 15 December 2020].

ENTSOG (2020). Mosahyc (Mosel Saar Hydrogen Conversion) | ENTSOG. [online] Available at: <https://www.entsog.eu/mosahyc-mosel-saar-hydrogen-conversion> [Accessed 15 December 2020].

Escobar, N. et al. (2020). Spatially-explicit footprints of agricultural commodities: Mapping carbon emissions embodied in Brazil's soy exports. In: Global Environmental Change, 62, 102067.

European Commission (2016). EU Reference Scenario 2016: Energy, transport, and GHG emissions trends to 2050. [online] https://op.europa.eu/en/publication-detail/-/publication/aed45f8e-63e3-47fb-9440-a0a14370f243/language-en/format-PDF/source-106883045 [Accessed 15 December 2020].

European Commission (2020). Amended proposal for a regulation of the European Parliament and of the Council establishing the Just transition Fund, 28.05.2020, COM(2020) 460 final.

European Parliament (2017). Food waste: The problem in the EU in numbers. [online] https://www.europarl.europa.eu/news/en/headlines/society/20170505STO73528/food-waste-the-problem-in-the-eu-in-numbers-infographic. [Accessed 10 December 2020].

Eurostat (2017). Agri-environmental indicator – Greenhouse Gas Emissions. Statistics explained. [online] https://ec.europa.eu/eurostat/statistics-explained/pdfscache/16817.pdf [Accessed 18 December 2020].

Faber, J. et al. (2012). Behavioural Climate Change Mitigation Options and Their Appropriate Inclusion in Quantitative Longer-Term Policy Scenarios – Main Report CE Delft.

Fantke, P. et al. (2016). Health impacts of fine particulate matter. In: Frischknecht, R., Jolliet, O. (eds.), Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1. Paris: UNEP/SETAC Life Cycle Initiative, pp. 76-99.

FAO (2007). Declaration of Nyéléni. [online] Available at: <https://nyeleni.org/IMG/pdf/DeclNyeleni-en.pdf> [Accessed 15 December 2020].

FAO (2014). SAFA guidelines: sustainability assessment of food and agriculture systems, Version 3.0. ed. Food and Agriculture Organization of the United Nations, Rome.

FAO (2018). The 10 elements of agroecology. Guiding the Transition to Sustainable Food and Agricultural Systems. Food and Agriculture Organisation of the United Nations. [online] http://www.fao.org/3/i9037en/I9037EN.pdf. [Accessed on 8 December 2020].

FAO (2020). Declaration Of Nyéléni | FAO. [online] Available at: <http://www.fao.org/agroecology/database/detail/fr/c/1253617/> [Accessed 15 December 2020].

Forbrukerrådet (2020). Cause For Complaint? - Forbrukerrådet. [online] Available at: <https://www.forbrukerradet.no/cause-for-complaint/> [Accessed 15 December 2020].

Frantzeskaki, N., Loorbach, D., & Kooiman, J. (2009). Transitions governance: Towards a new governance paradigm. Copenhagen: IRSPM. [online] https://repub.eur.nl/pub/37231/ [Accessed 11 December 2020].

Fraunhofer (2020). [online] Available at: <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/infomaterial/brochures/photovoltaik/20_en_ISE_Flyer_Agrar-PV.pdf> [Accessed 15 December 2020].

Fridstrøm, L., Østli, V., Johansen, K.W. (2016). A stock-flow cohort model of the national car fleet. In: European Transport Research Review, 8, p. 22.

Galli, A. et al. (2016). Questioning the Ecological Footprint. In: Ecological Indicators 69, pp. 224-232.

GE (2018). Rapport "Genève 2050". [online] Available at: <https://www.ge.ch/document/rapport-geneve-2050> [Accessed 16 December 2020].

Gillingham, K. & Palmer, K. (2014). Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence. In: Review of Environmental Economics and Policy, 8(1), pp.18-38.

Giljum, S. (2019). The impacts of data deviations between MRIO models on material footprints. In: Journal of Industrial Ecology, 23, pp. 946–958. https://doi.org/10.1111/jiec.12833.

Giovannini, E. et al. (2020). Time for transformative resilience: The COVID-19 emergency. In JRC Working Papers (No. JRC120489; JRC Working Papers). Joint Research Centre (Seville site). [online] https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/time-transformative-resilience-covid-19-emergency.

Gössling, S. (2013). Urban transport transitions: Copenhagen, city of cyclists. In: Journal of Transport Geography, 33, pp. 196-206.

Gössling, S. (2020). Why cities need to take road space from cars-and how this could be done. In: Journal of Urban Design, 25, pp. 443-448. [online] https://doi.org/10.1080/13574809.2020.1727318. [Accessed 15 December 2020].

Halbe, J., & Pahl-Wostl, C. (2019). A methodological framework to initiate and design transition governance processes. In: Sustainability, 11(3), p. 844. https://doi.org/10.3390/su11030844.

Harvey, D. (1973). Social justice and the city. Athens: Georgia University Press.

Heffron, R. J. & McCauley, D. (2018). What is the 'Just Transition'? In: Geoforum, 88, pp. 74-77.

Hertweck, F. (2020a). The Question of Land: Positions and Models. Zurich: Lars Müller Publishers.

Hertweck, F. (2020b). Dialektik der Kreativität. Eine kurze Geschichte der Kulturalisierung Berlin. In: ARCH+, no 241, pp. 151-160.

Hesse, M. (2015). Luxemburg – State of the Art. In: disP – The Planning Review 51(1), pp. 54-55.

Hesse, M., & Wong, C. M. L. (2020). Cities seen through a relational lens: Niche economic strategies and related urban development trajectories in Geneva (Switzerland), Luxembourg (Luxembourg) and Singapore. Geographische Zeitschrift, 108(2), pp. 74-98.

Hickel, J. (2019). Degrowth: a theory of radical abundance. In: real-world economics review, (87), pp. 54–68.

Hickel, J., & Kallis, G. (2020). Is green growth possible? In: New Political Economy, 25(4), pp. 469-486.

Hobson, K. & Lynch, N. (2016). Diversifying and de-growing the circular economy: Radical social transformation in a resource-scarce world. In: Futures, 82, pp. 15–25. doi: 10.1016/j.futures.2016.05.012.

Hoekstra, A. Y. & Wiedmann, T. O. (2014). Humanity's unsustainable environmental footprint. In: Science, 344(6188), pp. 1114-1117.

Holmgren (2009), D., Future Scenarios: How Communities Can Adapt to Peak Oil and Climate Change. Cambridge: Green Books.

Hopkins, R. (2011). The Transition Companion: Making Your Community More Resilient in Uncertain Times. Cambridge: Green books.

Hopkins, R. (2019). From What Is to What If: Unleashing the Power of Imagination to Create the Future We Want, White River Junction/ London: Chelsea Green Publishing.

Hoxha, A. & Christensen, B. (2018). The carbon footprint of fertiliser production: Regional reference values. Presented to the International Fertiliser Society, Proceedings 805, May. [online] https://www.fertilizerseurope.com/wp-content/uploads/2020/01/The-carbon-footprint-of-fertilizer-production_Regional-reference-values.pdf. [Accessed 8 December 2020].

IAASTD Global (2009). Agriculture as a Crossroads. International Assessment of Agricultural Knowledge, Science and Technology for Development. Global Report. Edited by McIntyre, B. D. et al. Washington D.C.: Island Press. [online] https://www.globalagriculture.org/fileadmin/files/weltagrarbericht/IAASTDBerichte/GlobalReport.pdf [Accessed 10 December 2020]

IEA (2020). IEA Sankey Diagram. [online] Available at: <https://www.iea.org/sankey/#?c=Luxembourg&s=Balance> [Accessed 15 December 2020].

ILR (2020). Rapport de l'Institut Luxembourgeois de Régulation sur ses activités et sur l'exécution de ses missions dans les secteurs de l'électricité et du gaz naturel. [online] https://assets.ilr.lu/energie/Documents/ILRLU-1685561960-831.pdf [Accessed 15 December 2020].

Indicators (2020). Indicators.Be - Income Inequality: S80/S20. [online] Available at: <https://indicators.be/en/i/G10_IIN/Income_inequality%3A_S80_S20> [Accessed 15 December 2020].

Inrix (2020). Scorecard. [online] Available at: <https://inrix.com/scorecard> [Accessed 14 December 2020].

Jackson, T. (2009). Prosperity without growth? The transition to a sustainable economy. London: Earthscan.

JRC (2010). Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions – Phase 1 (GGELS). Final Report. Joint Research Centre. Ispra: European Commission.

Junk, J., & Alves, B. (2020). Climate Change in Luxembourg. In: Kleeschulte, S. et al. (eds.), Hazard Mapping and Disaster Risk Assessment in Luxembourg: An integrated approach for cross-sectoral analysis at the country level. Final Report, Luxembourg.

Katsikis, N., Weichold, I., Hertweck, F. (2020). Composite Metabolic Landscapes in Luxembourg, Research Project in the Framework of the "Eco-Century Project" funded by Fondation Braillard, University of Luxembourg, Final Unpublished Report.

Kenis, A. & Lievens, M. (2016). Greening the Economy or Economizing the Green Project? When Environmental Concerns Are Turned into a Means to Save the Market'. In: Review of Radical Political Economics, 48(2), pp. 217–234. doi: 10.1177/0486613415591803.

Keßler, S. et al. (2020). Ecological Footprint – reloaded, IBLA, Luxembourg. [online] Available at: https://csdd.public.lu/content/dam/csdd/fr/actualites/2020/Report-Ecological-Footprint-Luxembourg-IBLA.pdf [Accessed 14 December 2020].

Kivimaa, P. et al. (2017). Experiments in climate governance – A systematic review of research on energy and built environment transitions. In: Journal of Cleaner Production, 169, pp. 17-29. https://doi.org/10.1016/j.jclepro.2017.01.027

Kolodziejczak, M. (2018). Food self-sufficiency in EU countries: An attempted projection to 2080. In: 27th International Scientific Conference, Agrarian perspectives XXVII, Food safety food security, September 2018, pp. 136-143.

König, A. et al. (2020), Nexus Futures. Scenarios for Luxembourg in 2045. Research Project to be published in 2021, University of Luxembourg.

Kuhnhenn et al. (2020). A Societal Transformation Scenario for Staying Below 1.5°C. [online] https://www.boell.de/sites/default/files/2020-12/A Societal Transformation Scenario for Staying Below 1.5C.pdf [Accessed on 10 December 2020]

Lam, D. P. M. et al. (2020). Scaling the impact of sustainability initiatives: A typology of amplification processes. In: Urban Transformations, 2(1), p. 3. [online] https://doi.org/10.1186/s42854-020-00007-9.

Lamker, C. & Schulze Dieckhoff, V. (2019). Mit oder gegen den Strom? Postwachstumsplanung in der Fishbowl. In: RaumPlanung, 201(2–2019), pp. 48–54.

Laurent, D. (2020). La sobriété dans les scénarios de transition. In: la Revue de l'Énergie n°648 janvier-février 2020, pp. 30-42.

Lefebvre, H. (1974). La production de l'espace. Paris: Anthropos.

Lehmann, L. M. et al. (2020). Productivity and Economic Evaluation of Agroforestry Systems for Sustainable Production of Food and Non-Food Products. In: Sustainability, 12(13), p. 5429.

Leick, A., Hesse, M., Becker, T. (2020). Vom „Projekt im Projekt" zur „Stadt in der Stadt"? Probleme der Governance und des Managements großer urbaner Entwicklungsvorhaben am Beispiel der Wissenschaftsstadt Belval, Luxemburg. In: Raumforschung & Raumordnung/Spatial Research & Policy 78(3), pp. 1-17. DOI: 10.2478/rara-2020-0009.

Leip, A. et al. (2015). Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. In: Environmental Research Letters, 10(11), 115004.

Linz, M. (2015). Suffizienz als politische Praxis – Ein Katalog. Wuppertal Spezial 49. Wuppertal Institut für Klima, Umwelt, Energie GmbH.

Linz, M. (2017). Wie Suffizienzpolitiken gelingen: Eine Handreichung. Wuppertal Spezial Nr. 52. Wuppertal Institut für Klima, Umwelt, Energie GmbH.

LIST (2020). SUCCESS. [online] List.lu. Available at: <https://www.list.lu/en/research/project/success/> [Accessed 15 December 2020].

Loorbach, D. (2020). Transforming climate governance? Why climate governance is failing and what to do about it. In: Hölscher, K. & Frantzeskaki, N. (eds.), Transformative Climate Governance: A Capacities Perspective to Systematise, Evaluate and Guide Climate Action. Berlin: Springer International Publishing, pp. 431-445. https://doi.org/10.1007/978-3-030-49040-9_13.

Loske, R. (2018). Luxemburgs Weg in eine klimafreundliche Zukunft: Eine gesellschaftspolitische Strategie. Im Auftrag des Ministère du Développement durable et des Infrastructures Département de l'Environnement. Presented at MDDI on 5.6.2018. Unpublished.

Madanipour, A., Shucksmith, M., Talbot, H. (2017). Locality and spatial justice: A conceptual framework. RELOCAL Working Paper Series (1). RELOCAL – Resituating the Local in Cohesion and Territorial Development.

Mader, C. (2013). Sustainability process assessment on transformative potentials: The Graz Model for Integrative Development. In: Journal of Cleaner Production, 49, pp. 54-63. [online] https://doi.org/10.1016/j.jclepro.2012.08.028. [Accessed 4 December 2020]

Mang, P., & Haggard, B. (2016). Regenerative development and design: A framework for evolving sustainability. Hoboken (New Jersey): John Wiley & Sons.

Max-Neef, M. (1995). Economic growth and "quality of life" a threshold hypothesis. In: Ecological Economics, 15, pp. 115-118.

McCrory, G. et al. (2020). Sustainability-oriented labs in real-world contexts: An exploratory review. In: Journal of Cleaner Production, 277, 123202. https://doi.org/10.1016/j.jclepro.2020.123202.

Meadows, D. (1999). Die Grenzen des Denkens. Wie wir sie mit System erkennen und überwinden können. Munich: oekom.

Meadows, D. (2020a). The Academy for Systems Change. 2020. Leverage Points: Places To Intervene In A System. [online] Available at: <http://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system> [Accessed 16 December 2020].

Meadows, D. (2020b). Grüne Industrie Ist Reine Phantasie. [online] FAZ.NET. Available at: <https://www.faz.net/aktuell/feuilleton/debatten/ein-gespraech-mit-dennis-meadows-gruene-industrie-ist-reine-phantasie-11980763.html> [Accessed 16 December 2020].

MECDD (2020). Strategie und Aktionsplan für die Anpassung an den Klimawandel in Luxemburg 2018 – 2023. Luxembourg.

MECO (2020). [online] Available at: <https://www.meco.lu/wp-content/uploads/2020/07/DEFINITIVE-PUBLIKATION-UMFRAGE_HP.pdf> [Accessed 16 December 2020].

Meinhertz, F., Fritz, L., Schneider, F. (2020). How values play into sustainability assessments: Challenges and a possible way forward. In: Binder, C. R., Wyss, R., Massaro, E. (eds.), Sustainability assessments of urban systems, Cambridge University Press, pp. 65-86.

Millennium Ecosystem Assessment (2005). Ecosystems and Human Wellbeing: Policy Responses Volume 3. Chapter 9: Nutrient Management: pp. 295-311. Primary Authors: Howarth, R. and K. Ramakrrshna. Eds. K. Chopra, R. Leemans, P. Kumar, and H. Simons. Washington DC: Island Press.

Millward-Hopkins, J. et al. (2020). Providing decent living with minimum energy: A global scenario. In: Global Environmental Change, 65, 102168.

Ministère de l'Agriculture, de la Viticulture et du Développement rural (2020). Rapport d'activité 2019. Luxemburg. [online] https://gouvernement.lu/fr/publications/rapport-activite/minist-agriculture-viticulture-protection-consommateurs/magri/2019-rapport-activite-ma.html. [Accessed 10 December 2020].

Monteiro, V. (2016). The impact of greenspace size on the extent of local nocturnal air temperature cooling in London. In: Urban Forestry & Urban Greening, 16, pp. 160-69.

Moore, C. et al. (2020). Vision or division? What do National Energy and Climate Plans tell us about the EU power sector in 2030? [online] https://ember-climate.org/wp-content/uploads/2020/10/Vision-or-Division-Ember-analysis-of-NECPs.pdf [Accessed 14 December 2020].

Mouvement écologique (2020). Neue ILRES-Umfrage zeigt: Menschen wollen kein Zurück in die Gesellschaft "Vor-Corona". [online] https://www.meco.lu/wp-content/uploads/2020/07/DEFINITIVE-PUBLIKATION-UMFRAGE_HP.pdf [Accessed 8 December 2020].

Myenergy (2020). [online] Clever Solar. https://www.myenergy.lu/de/cleversolar [Accessed on 5 December 2020].

natur & ëmwelt (2020). L'état De Conservation Des Habitats Naturels Et De La Faune & Flore Sauvages Au Luxembourg : UNE SITUATION ALARMANTE ! - Natur&Ëmwelt. [online] Available at: <https://www.naturemwelt.lu/letat-de-conservation-des-habitats-naturels-et-de-la-faune-et-de-la-flore-sauvages-au-luxembourg-une-situation-alarmante> [Accessed 14 December 2020].

Niccolucci, V., Pulselli, F.M., Tiezzi E. (2007). Strengthening the threshold hypothesis: economic and biophysical limits to growth. In: Ecological Economics, 60, pp. 667-672.

Observatoire de l'Habitat (2019a), La Note, no 23/February 2019.
http://observatoire.liser.lu/pdfs/Note23_A4.pdf

Observatoire de l'Habitat (2019b), Logement public (2020). Renforcer Le Logement À Coût Modéré. [online] Available at: <https://logement.public.lu/fr/actualites/2019/02/190228_Conference_de_presse_OBS.html> [Accessed 14 December 2020].

OECD (2020). Examens environnementaux de l'OCDE : Luxembourg 2020. Examens environnementaux de l'OCDE, Paris : Éditions OCDE. https://doi.org/10.1787/91951f4d-fr.

O'Neill, D. et al. (2018). A good life for all within planetary boundaries. Nature Sustainability, 1(2), pp. 88-95. [online] https://doi.org/10.1038/s41893-018-0021-4.

Othoniel, B. et al. (2019). An improved life cycle impact assessment principle for assessing the impact of land use on ecosystem services. In: Science of The Total Environment, 693, 133374.

Paccoud (2019). Foncièrement égoïstes, Antoine Paccoud in conversation with Bernard Thomas. In: Lëtzebuerger Land 6.12.2019.

Paech, N. (2010). Eine Alternative zum Entkopplungsmythos: Die Postwachstumsökonomie, In: Humane Wirtschaft, 5/2010, pp. 12-14.

Paech, N. (2012). Befreiung vom Überfluss: Auf dem Weg in die Postwachstumsökonomie. Munich: oekom.

Paech, N. (2013). Wer weniger kauft, hat mehr Zeit. In: Der kleine Bund vom 3.12.2013.

Paris, N. & Schneider, N. (2019). Le silence de l'effondrement. In: Robert Urbé (ed.), Caritas Sozialalmanach 2019, pp. 143-173.

Penha-Lopes, G. & Henfrey, T. (2019). Reshaping the future: How local communities are catalysing social, economic and ecological transformation in Europe. Brussels: ECOLISE. [online] https://www.ecolise.eu/wp-content/uploads/2016/02/Status-Report-on-Community-led-Action-on-Sustainability-Climate-Change-in-Europe-2019.pdf.

Pinno, A. (2020). Es braucht eine positive Vision. In: taz 2 January 2020.

Rabhi, F. (2010). Sobriété heureuse. Paris: Actes sud.

Rafii-Tabrizi, S. (2020). Smart Electrical And Thermal Energy Supply For Nearly Zero Energy Buildings. [online] Hdl.handle.net. Available at: <http://hdl.handle.net/10993/44256> [Accessed 15 December 2020].

Raworth, K. (2017). Doughnut Economics: Seven ways to think like a 21st-century economist. White River Junction (Vermont): Chelsea Green Publishing.

Raworth, K. (2020). Introducing the Amsterdam City Doughnut. [online] Available at: <https://www.kateraworth.com/2020/04/08/amsterdam-city-doughnut/> [Accessed 14 December 2020].

Reckinger, R., Kapgen, D., Korjonen, H. (2020): An infographic synopsis of Luxembourg's Food System. In: Forum für Politik, Gesellschaft und Kultur in Luxemburg, n° 408, July 2020, pp. 39-42.

Rifkin, J. et al. (2016), The Third Industrial Revolution Strategy. Study For the Grand Duchy of Luxembourg. [online] Available at: <https://www.troisiemerevolutionindustrielle.lu> [Accessed 15 December 2020].

Ritchie, H. (2019). How Do CO2 Emissions Compare When We Adjust For Trade? [online] Our World in Data. Available at: <https://ourworldindata.org/consumption-based-co2> [Accessed 15 December 2020].

Rossi, A. (1966). L'Architettura della città. Genere: Saggio.

Rugani, B., Marvuglia, A., Pulselli, F. M. (2018). Predicting Sustainable Economic Welfare–Analysis and perspectives for Luxembourg based on energy policy scenarios. In: Technological Forecasting and Social Change, 137, pp. 288-303.

Sala, S., & Castellani, V. (2019). The consumer footprint: Monitoring sustainable development goal 12 with process-based life cycle assessment. In: Journal of Cleaner Production, 240, 118050.

Sandström, V. et al. (2018). The role of trade in the greenhouse gas footprints of EU diets. In: Global food security, 19, pp. 48-55.

Schader, C. et al. (2015). Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. In: Journal of the Royal Society Interface, 12(113), 20150891.

Schader, C. et al. (2016). Using the Sustainability Monitoring and Assessment Routine (SMART) for the Systematic Analysis of Trade-Offs and Synergies between Sustainability Dimensions and Themes at Farm Level. In: Sustainability, 8(3), p. 274.

Schmelzer, M. & Vetter, A. (2019). Degrowth/Postwachstum zur Einführung. Hamburg: Junius.

Schmid, B. (2019). Degrowth and postcapitalism: Transformative geographies beyond accumulation and growth. In: Geography Compass, 13(11). doi: 10.1111/gec3.12470.

Schneidewind, U. & Zahrnt, A. (2014). The politics of sufficiency – making it easier to live the good live. Munich: oekom.

Schulz, C. (2020). Land for Post-Growth, in: Hertweck, F. (ed.), Architecture on Common Ground. The Question of Land: Positions and Models. Zurich: Lars Müller Publishers, pp. 140-148.

Schumacher, E. F. (1973). Small is beautiful: A study of economics as if people mattered. New York: Random House.

Sieverts, T. (1997). Zwischenstadt: Zwischen Ort und Welt, Raum und Zeit, Stadt und Land. Wiesbaden/Braunschweig: Vieweg.

Soja, E. (2010). Seeking spatial justice. London: Minnesota University Press.

Stadler, K. et al. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. In: Journal of Industrial Ecology 22, pp. 502-515, doi:10.1111/jiec.12715.

Stadler, K. et al. (2020). EXIOBASE 3. [online] Zenodo. Available at: <https://zenodo.org/record/4277368> [Accessed 15 December 2020].

Start Luxembourg Fund (2020). Investment Funds In Luxembourg. [online] Available at: <https://www.startluxembourgfund.com/investment-funds-in-luxembourg> [Accessed 14 December 2020].
STATEC (2013). The Housing Situation: Residential Buildings, Households, Homeowners And Tenants. [online] Available at: <https://statistiques.public.lu/en/news/population/population/2013/02/20130213/index.html> [Accessed 15 December 2020].

STATEC (2020a). Employment, unemployment and unemployment rate per month (seasonally adjusted) 1995 – 2020. https://statistiques.public.lu/stat/TableViewer/tableView.aspx?ReportId=12948&IF_Language=eng&MainTheme=2&FldrName=3

STATEC (2020b). STATEC, 2020. Population density by canton and municipality (Inhabitants per km²) 1821 - 2020. https://statistiques.public.lu/stat/TableViewer/tableView.aspx?ReportId=12862&IF_Language=eng&MainTheme=2&FldrName=1https://statistiques.public.lu/stat/TableViewer/tableView.aspx?ReportId=12862&IF_Language=fra&MainTheme=2&FldrName=1

STATEC (2020c). Domestic payroll employment by citizenship and country of residence 1995 – 2020. https://statistiques.public.lu/stat/TableViewer/tableView.aspx?ReportId=12916&IF_Language=eng&MainTheme=2&FldrName=3&RFPath=92

STATEC (2020d). Rapport PIBien-Être. Institut national de la statistique et des études économiques (STATEC).

STATEC (2020e). Parc des véhicules automoteurs routiers immatriculés par type de véhicule 1936 – 2020. https://statistiques.public.lu/stat/TableViewer/tableViewHTML.aspx?sCS_ChosenLang=fr&ReportId=13499

STATEC (2020f). Logements au Luxembourg: autant de maisons que d'appartements. https://statistiques.public.lu/fr/actualites/entreprises/logement/2017/07/20170721/index.html

STATEC (2020g). Supply balance sheets for cattle and pigs 1999 - 2019 https://statistiques.public.lu/stat/TableViewer/tableView.aspx?ReportId=13371&IF_Language=eng&MainTheme=4&FldrName=2&RFPath=7276

STATEC (2020h). Emploi statutaire dans le secteur public 1960 - 2017 https://statistiques.public.lu/stat/TableViewer/tableView.aspx?ReportId=12921&IF_Language=fra&MainTheme=2&FldrName=3&RFPath=92

STATEC (2020i). Parc des véhicules automoteurs routiers immatriculés par type de véhicule 1936 – 2020. https://statistiques.public.lu/stat/TableViewer/tableView.aspx?ReportId=13499&IF_Language=fra&MainTheme=4&FldrName=7&RFPath=7049%2C13898

STATEC & LISER (2020a). And housing prices continue to rise by an average of 6% each year. Le Logement Chiffres. [online] Available at: <http://observatoire.liser.lu/pdfs/Logement_chiffres_2019T4.pdf> [Accessed 15 December 2020].
EU-SILC 2010-2017.

Statista (2020). Installed solar photovoltaics capacity per capita in the European Union (EU-28) in 2019, by country. [online] https://www.statista.com/statistics/612412/installed-solar-photovoltaics-capacity-eu/ [Accessed on 15 December 2020].

Statistics Poland (2018). Gospodarka Mieszkaniowa W. Latach 2013-2017. [online] Available at: <https://stat.gov.pl/obszary-tematyczne/infrastruktura-komunalna-nieruchomosci/nieruchomosci-budynki-infrastruktura-komunalna/gospodarka-mieszkaniowa-w-latach-2013-2017,11,1.html> [Accessed 15 December 2020].

Steinsland, C. et al. (2018). The climate, economic and equity effects of fuel tax, road toll and commuter tax credit. In: Transport Policy, 72(C), pp. 225-241.

Strasser, T., de Kraker, J., Kemp, R. (2019). Developing the transformative capacity of social innovation through learning: A conceptual framework and research agenda for the roles of network leadership. In: Sustainability, 11(5), 1304. [online] https://doi.org/10.3390/su11051304. [Accessed 8 December 2020].

Tainio, M. et al. (2016). Can air pollution negate the health benefits of cycling and walking? In: Preventive medicine, 87, pp. 233-236.

TESS project (2016). Impact analysis of community-based initiatives, including carbon reduction assessment (Deliverable 2.4). http://www.tess-transition.eu/wp-content/uploads/2016/06/2016_06_20_Deliverable_2.4_FINAL.pdf.

The Atlas (2015). Connected Devices Per Capita. [online] Available at: <https://theatlas.com/charts/EJjL-dqR> [Accessed 15 December 2020].

The Shift (2020). The Shift Project. Plan De Transformation De L'économie : Focus Sur L'administration Publique. [online] Available at: <https://theshiftproject.org/plan-de-transformation-de-leconomie-focus-sur-ladministration-publique/> [Accessed 15 December 2020].

Tomtom (2020). Luxembourg Traffic. [online] Available at: <https://www.tomtom.com/en_gb/traffic-index/luxembourg-traffic/>

[Accessed 14 December 2020].

TU Wien (2019). The Material Flow Analysis Portal. [online] https://www.stan2web.net/infos/about-stan. [Accessed 12 December 2020].
UL (2020). Szenarien - Sustainability Science. [online] Available at: <https://sustainabilityscience.uni.lu/szenarien/> [Accessed 16 December 2020].

Vetter, A. (2017). The Matrix of Convivial Technology e Assessing technologies for degrowth. In: Journal of Cleaner Production, no 197. DOI: 10.1016/j.jclepro.2017.02.195.

Wahl, D. C. (2016). Designing regenerative cultures. Charmouth: Triarchy Press.

Welzer, H. (2020). Alles könnte anders sein. Frankfurt a. M.: S. Fischer Verlag.
Wernet, G. et al. (2016). The ecoinvent database version 3 (part I): overview and methodology. In: The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230.

WIKUE (2020). Wie Suffizienzpolitiken Gelingen. [online] Wupperinst.org. Available at: <https://wupperinst.org/a/wi/a/s/ad/3749/> [Accessed 16 December 2020].

Widmer, H. E. et al. (2016), Nach Hause kommen. Nachbarschaften als Commons. Zurich: ecolog.

Wolfram, M. (2016). Conceptualizing urban transformative capacity: A framework for research and policy. In: Cities, 51, pp. 121-130. https://doi.org/10.1016/j.cities.2015.11.011 [Accessed 18 December 2020].

Wolfram, P. et al. (2020). Material efficiency and climate change mitigation of passenger vehicles. Journal of Industrial Ecology [online] https://doi.org/10.1111/jiec.13067 [Accessed 15 December 2020].

You, W. & Henneberg, M. (2016). Meat consumption providing a surplus energy in modern diet contributes to obesity prevalence: an ecological analysis. In: BMC Nutrition, 2(1), p. 22.

Zahlen, P. (2014). Regards sur la surface des logements. No 27/2014. STATEC white paper. [online] https://statistiques.public.lu/fr/publications/series/regards/2014/27-14-log-surf/index.html.

2000m2 (2020). 2000M2.Lu. [online] Available at: <https://www.2000m2.lu/> [Accessed 15 December 2020].

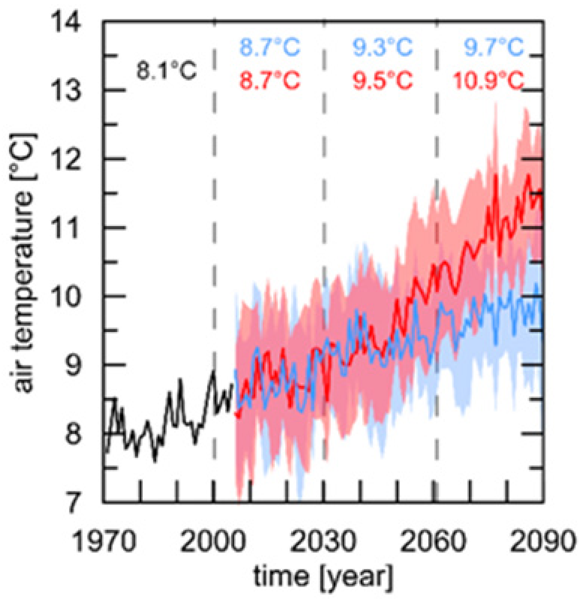


Figure A1. Multi-model ensemble of mean annual air temperature values for Luxembourg based on two different Representative Concentration Pathways (RCPs) (4.5 = blue; 8.5 = red). Spread is defined via +/- one standard deviation of the ensemble (Junk et al., 2019)

Future climate conditions for Luxembourg and expected impacts by sector

To assess the future climate condition for Luxembourg time series derived from a multi-model ensemble of climate change projections from the Coordinated Regional Climate Downscaling Experiment (CORDEX) project of the World Climate Research Programme (WCRP). The regional climate model (RCM) data are based on simulations from the EURO-CORDEX initiative. This is the European branch of the CORDEX project. Data is made available on the data nodes of the Earth System Grid Federation (ESGF) model data dissemination system. Figure A1 highlights the results of the multi-model ensemble for mean annual air temperatures Luxembourg. The future climate projections of the nested regional climate model approaches show increases of the mean annual air temperatures from 8.1°C in the reference period to 9.7°C and 10.9°C depending on the underlying RCP. All differences between the reference period and the three different future time spans and two RCPs were statistically significant ($p < 0.001$) (Junk et al., 2019).

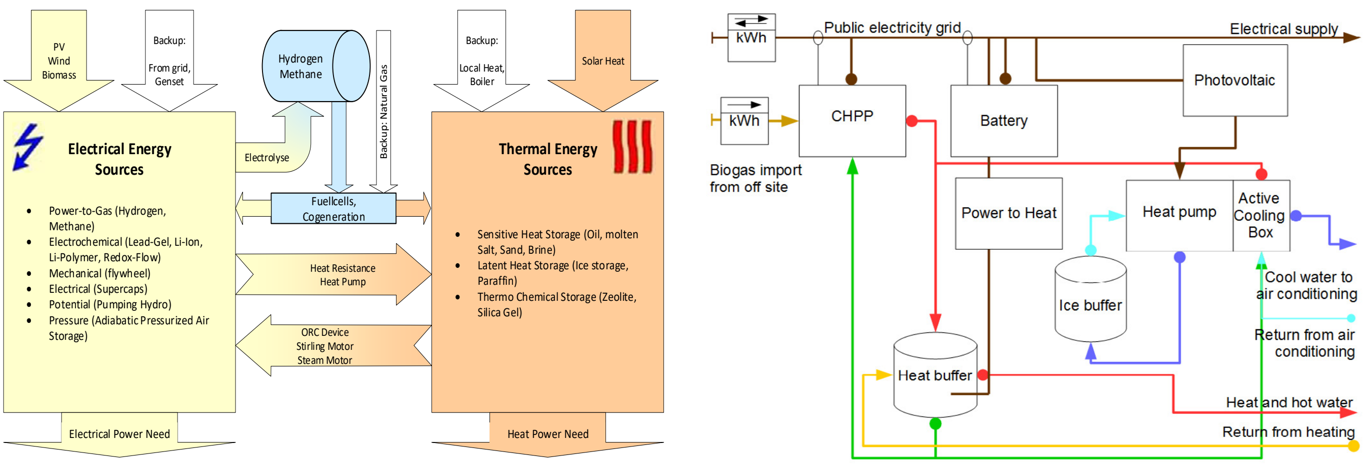


Figure A2. Industrial Power Conversion Units, and principle of a modular energy network for the coverage of eco-cities thermal and electrical need

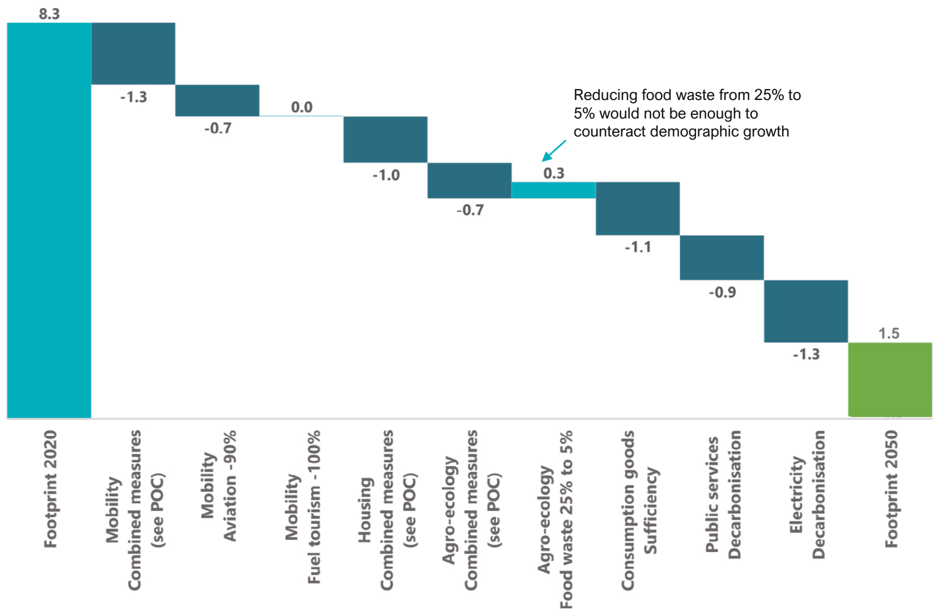


Figure A3. Impact of decarbonization measures, including the three proofs-of-concept (mobility, housing, agro-ecology, which are sets of combined measures), scope: resident consumption only.

Old paradigm/mental model	New paradigm/mental model	Actions to implement	Expected positive effects
Vehicles ownership is the main model.	Mobility is seen mainly as a service. Vehicle ownership is no longer the main model.	Mobility mainly takes place using shared vehicles, most of which are not owned by anyone, but are part of a shared service platform operated by a service partner but governed collectively.	Optimisation of materials' use (considering that vehicles are materials' sinks, because they are used only 5% of the time and are mobilised in parking lots 95% of the time.)
Cities are designed to ensure firstly car transit, car stationing and pedestrians are not the main subjects in the mind of the planners.	Cities are designed to ensure firstly space for pedestrians, enjoyable spaces for citizens.	Roads and car parking space is extremely downsized. The freed space is reused in equitable ways.	Cities are more liveable, and citizens feel a better "sense of space" and belonging to their urban community of people.
Land use plans are characterized by a division of functions and generate monofunctional zones and areas.	Land use plans are radically diversified, multifunctional and small grained.	New urbanistic and architectural typologies are developed which integrate diverse functions and activities.	Less fossil fuelled mobility, more time, more social coherence.
Work is an activity that mainly takes place in an office and every worker has his/her own personal physical space at the office.	Work takes place mostly remotely (for job categories that can be delivered in teleworking mode) or in shared office spaces where every person has not an assigned personal office space.	Boosting of teleworking as companies' policy and creation of office hubs with shared office spaces, open for different uses in the evenings and on the week-ends.	Decrease of transborder commuting and related congestions and emissions. Improvement of work-life balance.
Energy is produced mainly from fossil fuels, distributed by a central actor., with a time-invariant pricing structure.	Energy is produced from renewable sources, including at small scale	Energy decentralization, including modular energy conversion devices. Energy tariffs vary over time.	Citizens are prosumers. They have interest in producing and consuming energy in the most efficient way. They collaborate in maintaining the stability of the grid, using their electric car batteries as energy storage.

Figure A4. Mental models that will be leveraged and changed in our vision for Luxembourg society in 2050.
For example, "Library of Things": https://www.facebook.com/watch/?v=567183433876612

Nature is considered as an external element in the urban environment.	Nature is an integral part of the urban environment and is used as a tecno-ecological component to perform certain technical functions, such as purifying the air or delaying and dampening flood peaks.	Increased space dedicated to urban parks, gardens, parks, integration of urban nature-based or nature-inspired (biomimicry) solutions (green roofs, community gardens, etc.).	Improvement of aesthetic value in cities, sense of well-being for people (also linked to the increased use of shared and public gardens).
Objects' ownership is the main model. Tools and pieces of equipment are owned by people in an exclusive way. Expertise is a personal asset; if someone needs it, he/she has to pay.	Ownership and exclusivity are no longer the model. Objects are shared and used by people only occasionally, when needed. Expertise is shared.	Creation of objects' sharing platforms and spaces , but also "convivial technology" platforms (collaborative workshops, repair cafes, time banks, etc). Renaissance of the commons in terms of spaces and resources. Ground leases and Cooperatives	Circular use of materials Increased sense of community
Food is only produced by farmers in the fields. Only individual taste and health considerations determine diets.	Food can also be produced locally and by residents. Sustainability also influences diet choices.	Implementation of vertical gardens, urban agriculture, community-supported agriculture. Reduced consumption of meat products that contribute heavily to GHG emissions.	Increased food sovereignty, multifunctional use of space (which is an important resource as well), sustainable diets

Amplifiers - participatory approaches, integrative development, transition governance, capacity building

The European project TESS (Towards European Societal Sustainability) researched social innovations of grassroots initiatives with the goal to support both policy makers and community activists working on the low-carbon transition. The project developed the first cross-sectoral framework for GHG accounting specifically for community-based initiatives. With this tool, the project quantified the carbon emission reduction per beneficiary of more than 50 community-based initiatives in 6 European countries, according to their domain of activity: food, transport, energy or waste. The emission reductions have been calculated in relation to a baseline scenario corresponding to standard practices and supplies in the respective domain and country. An average reduction between 80 and 100% could be achieved in the domains of distribution of (organic) food, zero-carbon transport of goods and persons, provision of renewable heat and electricity, and repair/reuse of consumer goods. As in our own calculation, the most important contribution to the reduction of the per capita carbon footprint could be made in the domains of energy, almost 25% through renewable electricity from community energy initiatives and 11% for zero-carbon transport solutions for persons (more details see TESS project 2016:101).

But collective community-based transition solutions do not only deliver those targeted benefits to individual beneficiaries, they also support longer-term behavioural and lifestyle changes, in particular of the citizens that actively participate in co-creating and delivering those solutions, supporting each other in the process. They also generate multiple other benefits in their communities pertaining to social resilience, for instance social inclusion and solidarity and the diffusion of innovative practices (Penha-Lopes & Henfrey, 2019). In Luxembourg, the collaboration between citizen transition initiatives and municipalities has been prototyped in the climate pact 1.0 and will become more prominent in the climate pact 2.0. However, as explained in the initial problem statement, the existing governance structures and processes in Luxembourg and the Greater Region are not particularly conducive for a genuine transition governance that invites and scales stakeholder and citizen participation to the required levels and across the entire functional space.

We therefore include in our mix of interventions a focus on participatory transition governance, monitoring and action (Halbe, J., & Pahl-Wostl 2019). For the above-described accelerating and amplifying effects of community-based solutions on the decabornisation pathway to take root, it would be necessary to create a "Transition Hub" in basically each neighbourhood of the bigger cities, in each of the smaller towns and in each rural region. Transition Hubs invite any citizen, informal group or organisation residing or operating in that local area to engage in jointly exploring, designing, developing, testing, scaling and monitoring interventions that advance the socio-ecological transition. from multiple small projects to bigger ones, depending on the capacity a Transition Hub manages to attract and pool. As they are not tied to administrative boundaries, they can choose the most suitable geographical scope for each transition project. Transition Hubs interweave the different types of knowledge and experience from across sectors, households, businesses, civil society, public institutions, education and research, and make them useful for finding and exploiting, at each stage of the decabornisation path, the most effective leverage points in the respective local context. Transition Hubs need professional facilitators and coordinators versed in the international state of the art of stakeholder involvement and co-creation methodologies that give voice to all involved regardless their background and experience and that favour innovative, locally adapted solutions that actually work in the long run.

Once the local Transition Hubs start to form a network across the functional region, they can learn from each other's transition projects and hence further accelerate the transition through transfer of knowledge and practices. In the countries around Luxembourg there are various examples, networks and frameworks already that could help inform the creation of Transition Hubs and a Transition Hub network in the Luxembourg cross-border region, including:

- the Amsterdam Doughnut Coalition (https://amsterdamdonutcoalitie.nl) connected through DEAL, the Doughnut Economics Action Lab (https://doughnuteconomics.org), to emerging coalitions in other cities and regions worldwide likewise adopting the Doughnut Economics framework;
- the multiple award-winning BedZed (Beddington/London zero energy development) neighbourhood (https://www.zedfactory com/bedzed) that was a frontrunner 20 years ago and that gave rise to the One Planet Living framework and the associated WWF supported global network of One Planet Living site developments (https://www.bioregional.com/one-planet-living), which had also inspired the Hollerich Village vision in Luxembourg (that couldn't be realised, though);
- the 14 real-world laboratories (BaWü Labs) in which citizens and researchers collaborate with other stakeholders on system innovations, supported 2015-2019 by the ministry of science and research of the Land Baden-Württemberg, and which are now part of the quickly expanding German Network of Real-world Laboratories (https://www.reallabor-netzwerk.de);
- the Swiss network of "2000 Watt Society" sites (https://www.2000watt.swiss/english.html), a framework originally proposed by the ETH Zürich;
- the permaculture LAND (Learning and Demonstration) Centres in the UK, visited so far by over 40.000 people searching for inspiration how permaculture design works in practice in multiple settings and at different scales (https://www.permaculture.org.uk/land-centres);
- the Lorraine Smart Cities Living Lab (https://erpi.univ-lorraine.fr/fr/projects/LSCLL) that is an accredited member of the European Network of Living Labs (https://enoll.org) since 2010 and co-founder of the Living Labs France network.
- the Impact Hub Vienna (https://vienna.impacthub.net) is a co-working space, accelerator and diverse community of founders, creatives, investors, established companies and NGOs developing entrepreneurial solutions for a more inclusive, sustainable world – the Vienna Hub is connected to other Impact Hubs through a global network (https://impacthub.net).

This list is not exhaustive but it shows that relevant frameworks, networks, hubs and labs which invite boundaryless participation and co-creation for advancing the sustainability transition in specific local and regional contexts abound everywhere around Luxembourg, while Luxembourg is not actively involved in any of those streams. If Luxembourg seeks to become an international model for the zero-carbon transition, it needs first of all to catch up on its neighbours on those new participatory formats for designing and steering its implementation.Besides local Transition Hubs and their network, we also suggest creating and sustaining open cross-border / cross-sector System Innovation Platforms for each transition domain. For our focus domains this would mean a platform for:

- spatial justice, multifunctional land use & building retrofitting
- participatory energy transition and energy prosumers
- regional circular and sharing economy (which could include the existing wood cluster)
- agroecology and food sovereignty (connected to the national/ cross-border Food Council)

The local Transition Hubs could then call on the expertise and innovations pooled and further developed in the domain-specific platforms. Both System Innovation Platforms and local Transition Hubs would become further enhanced by establishing respective transformative research programmes through the FNR, calling for the application of participatory research formats (e.g. participatory action research, real-world laboratory or living lab methodologies) at hyperlocal (building), local (neighbourhood) and cross-border regional levels and thus transforming research investments in a direct contribution to country's and the cross-border region's zero-carbon transition. Transformative/participatory research programmes:

- participatory planning & multifunctional retrofitting
- zero carbon community energy systems
- sustainable and resilient food systems & regenerative carbon capturing agriculture
- regional sharing platforms & circular supply chains
- participatory transition governance & monitoring

As there is little capacity yet for rolling out such Transition Hubs and System Innovation Platforms in the functional region of Luxembourg, capacity building measures need to be taken, including:

- mapping entrepreneurial pioneers, civic initiatives and related stakeholders for identifying "transition hotspots" on which support could be focused in a first phase;
- creating and expanding a Community of Practice of transition facilitators in the region;
- supporting the development of Transition Hubs as actual locations such as co-working spaces, fab labs, maker spaces, repair cafés or "maisons de la transition" (see MESA in Esch/Alzette as a transferable model for the latter in Luxembourg https://www.transition-minett.lu/mesa-presentation);
- setting-up a flexible multi-partner blended (on-line/on-site) transition learning delivery system for all age and target groups,

within and across the transition domains (i.e. food, energy, housing etc. and systems design/systemic interventions);
- actively shaping the emergence of new transition professions, such as climate coaches, transition trainers, facilitators of cross-sector dialogues, transition hub coordinators, transition researchers, transition monitoring experts, system innovation transfer agents, and so on.
- evolving and integrating existing pacts (e.g. climate pact) into transition pacts at all levels, from local to cross-border.

The combination of these capacity building approaches create:
- the physical and virtual places for all interested contributors to meet and work together on the transition;
- the safe mental and relational spaces that allow shifting the imagination beyond the usual tracks;
- the facilitated, participatory practices of exploring the space of possibilities and making new experiences together,
- the pacts that enshrine the combined commitments of stakeholders across all sectors catalysing imagination into action.

These are key ingredients for supporting shifts in the collective imagination and action capacity (see https://www.robhopkins.net/2020/06/30/introducing-the-imagination-sundial) and for amplifying progress on the transition pathway through participatory approaches (Lam et al 2020).

Scenarios and prospects

Scenarios do not attempt to predict the future, but instead offer pictures of very different possible futures. Scenario-sets open up perspectives on diverse development paths and possible disruptive events we may need to brace for. As such they offer an excellent backdrop to develop visions. In the present visioning study we refer to two sets of scenarios: (a) the greater Geneva scenarios developed to address issues of territorial planning in a budding cross-border metropolis, and (b) national scenarios for the engagement with water and land in Luxembourg in 2045, that also payed attention to the spatial planning dimension. As Greater Geneva presents many similar aspects to the functional space of Luxembourg, much of the work pertaining to Geneva will also be relevant to Luxembourg.

The Haute École de Gestion de Genève and numerous thinkers have recently developed a set of four scenarios for the urban development of their trans-border territory in 2050 (GE 2018). Their first scenario "Une métropole, des territoires", a sort of Brown-Tech-Scenario, assumes an ongoing strengthening of the core city's influence, whilst peripheral regions continue to develop in a somewhat uncoordinated manner. Given its status as a global city of international institutions and financial services, the central city would benefit from this development and continue to grow. Limited by the small surface area, however, the incoming population would increasingly settle in the cross-border hinterland, amplifying the existing differences. The infrastructures (of the cross-border mobility and other) would come under increasing strain, leading to frequent overload and blockages. The impasse would largely reflect the lack of adequate metropolitan governance solutions for the cross-border region as a whole. Victims of the success of the core city would thus be middle classes and in particular working commuters which would be pushed further afield, while the land and real estate owners would continue to benefit from the trend. This forecast paints a negative picture of the business-as-usual approach, owing to the high social and environmental costs.

The second scenario "Décroissance économique … et développement humain" illustrates what might happen if sole focus is placed on Green Tech, based on "clean energy" (hydro and renewables). With the increasing digitalization, mechanisation and automation of the economy, and with an emphasis on clean energy solutions (the spread of electric cars, the block-chain technology, artificial intelligence, 3D printers, heat pumps, home batteries, and so on), it is foreseeable that electricity supply systems wouldn't be able to support the escalating demand. As a consequence, the population would need to consume less, including digitally, and to transform energy-intensive globalised industries into labour-intensive, regional ones. Sharing and solidarity would resurface as essential social values. This wouldn't necessarily mean a demographic shrinkage, on the contrary; the attractiveness of Geneva would lead to a further demographic increase, rejuvenating the population. The Green Tech ideology could thus ironically lead to a positive post-growth scenario, but only under severe energy shortages. For the city, it is rather likely that abundant and cheap fossil energy will continue to be available, dashing hopes of a positive future with the Green Tech.

A third scenario *“Prix du baril et hautes tensions”*, roughly equivalent to David Holmgren's Life-Boats-scenario, depicts a dystopian future. It assumes resource and energy shortages coupled with a worsening of the climate crisis, which would cause global economic collapse and geopolitical chaos. Locally, the global instability would result in unpredictable demographic developments (such as uncontrollable influx of refugees), as well as highly volatile economic and political situations (broken supply chains, surging commodity prices, collapse of existing governance arrangements, and so on).

For Luxembourg, more recently, in the Nexus Future Project a participatory process coordinated by Ariane König and a team of researchers in sustainability science at the University of Luxembourg (https:\\sustainabilityscience.uni.lu) was the basis to develop a set of three scenarios for the country in 2045 with an emphasis on water and land use. The first scenario “smart sustainability” is kept close to prior work on the third industrial revolution. Internationally political and economic interests are well aligned. This scenario relates to the previous described scenario for Geneva with an accent on Green Technologies, with the aim of “creating wealth through growth of a smart and regenerative circular economy” and predicts more power for multinational companies. Although much capital is being invested in infrastructure and production processes to regenerate renewable resources such as water and soil, ecosystems will be threatened more than ever in 2045 and biodiversity will continue to decline and ecosystems start collapsing in Luxembourg as well as throughout Western Europe. Despite high efficiency gains, rebound effects are causing an increase in water pollution, forest dieback, soil degradation and air pollution. Urban sprawl is estimated at a further land consumption of 5,500 ha. In this green tech scenario, a population increase of 1.3 million inhabitants is assumed for 2045 and economic growth is projected.

The second scenario “common good” describes a regionalised Europe and Luxembourg. In order to compensate for decreasing public services due to public funds five regions largely organised around today’s water and waste syndicates strive to allow for good social integration in a community and fulfilling leisure activities with a healthy relationship to nature are recognised as the basis for well-being. Risks of regional rivalries and tensions in view of scarce resources and continuing pollution are however looming. In this world, the local turn prevails: the economy depends mainly on local initiatives, markets and production cooperatives, communities join forces and create local currencies. Regional and local energy, water and food supplies are becoming commonplace, and cooperatives of local producers ensure locally fair distribution. Economic development is limited by access to renewable resources such as water, soil and energy, and quality of life is partly determined by local differences in access to such resources. This also leads to conflicts between local communities and communities, for example over the protection of springs and rivers. Urban sprawl is being stopped, the population is estimated at 933,000, and the economic growth rate is increasing from 1.0% to 1.5%.

The third scenario “web of life” , assumes disastrous consequences of global warming for the region, such as forest dieback, against which the state tries to counteract through a directive policy. Land will be purchased and leased under nature conservation conditions. All urban development is bunched around a central corridor along the Alzette, with sophisticated grids and infrastructures, whilst rural areas are reserved for a larger ‘wilderness zone’ and non-invasive ecotourism. In all three scenarios, the public income and expenditures have to be fundamentally restructured. In this scenario the receipt of a conditional basic income is bound to conditions of engaging in regenerative work for the biosphere, also allowing subsistence crop cultivation for own consumption in public and private agro-forest and permaculture areas that flank the urban corridor. While commuter frequency and mobility in general are declining sharply, citizens are turning into prosumers in order to cover their own needs for energy, water and food. As a result, the population is growing much more slowly than today, reaching 780 000 inhabitants in 2045.

A review of the various scenarios shows the fact that when both quantitative and qualitative data from diverse parties is drawn upon all scenarios contain some uncomfortable as well as some desirable developments. These scenarios are not about predicting the future as nobody has a crystal ball or, as Matthias Horx would say: Future does not exist. Rather, it is about spinning the various strategies, approaches and projects and breaking down their effects in time and space without pursuing an exhaustive claim. In view of these scenarios, it seemed important to us to clarify the relationship of our prospects to technological developments on the one hand, through scepticism about both supposedly promising effects and their implementation, and to assume a plausible value for demographic growth. Since our prospects are close to this second scenario with the hypothesis of a local turn, cooperative communities in terms of housing, food and production, we also accept its assumption regarding demographic growth. There are however also relevant elements of the other scenarios – such as the spread of prosumerism and the drop of commuting in the “web of life” scenario.

Thus, while our vision is based on the set of interventions that form our decarbonisation path as well as our guiding principles illustrated in the previous section, our vision is also informed by (1) the different scenarios described above that claim a relevant degree of coherence; (2) different sources pursuing a similar position on the socio-ecological transition (Widmer 2016, Pinno 2020, Holmgren 2009); (3) different works already carried out by the team (Research Program “Ignis Mutat Res. Penser l’architecture, la ville et le paysage au prisme de l’énergie”, Consultation du Grand Genève); and (4) the plausibility of a desired imaginary in order to achieve the objectives (zero emissions, resilience, social cohesion). It should be noted that there are different ways to reach the same goal. We have intentionally included a series of elements in our prospects whose potential for reaching the policy goals are yet to be discovered and understood in the contemporary policy arena.

Master in Architecture European Urbanisation & Globalisation
University of Luxembourg
MasterArchitecture.lu

Research in teaching

The studio aims to contribute to the ecosystem of studies around the “Luxembourg in Transition” call for tenders, which calls for regional development, urban planning and architectural visions for the functional space of Luxembourg, with the aim to address the ecological challenges of the 21st century and respond to the changing climatic conditions.

The studio blends the boundaries between architecture, planning, geography and territorial development and touches upon issues of social economic and ecological organisation. It aims to develop a platform for analysis and exploration of a series of scenarios of spatial development, responding to the intensive population and economic growth patterns of the Luxembourg region, and its largely unsustainable – both socially and ecologically – spatial development condition.

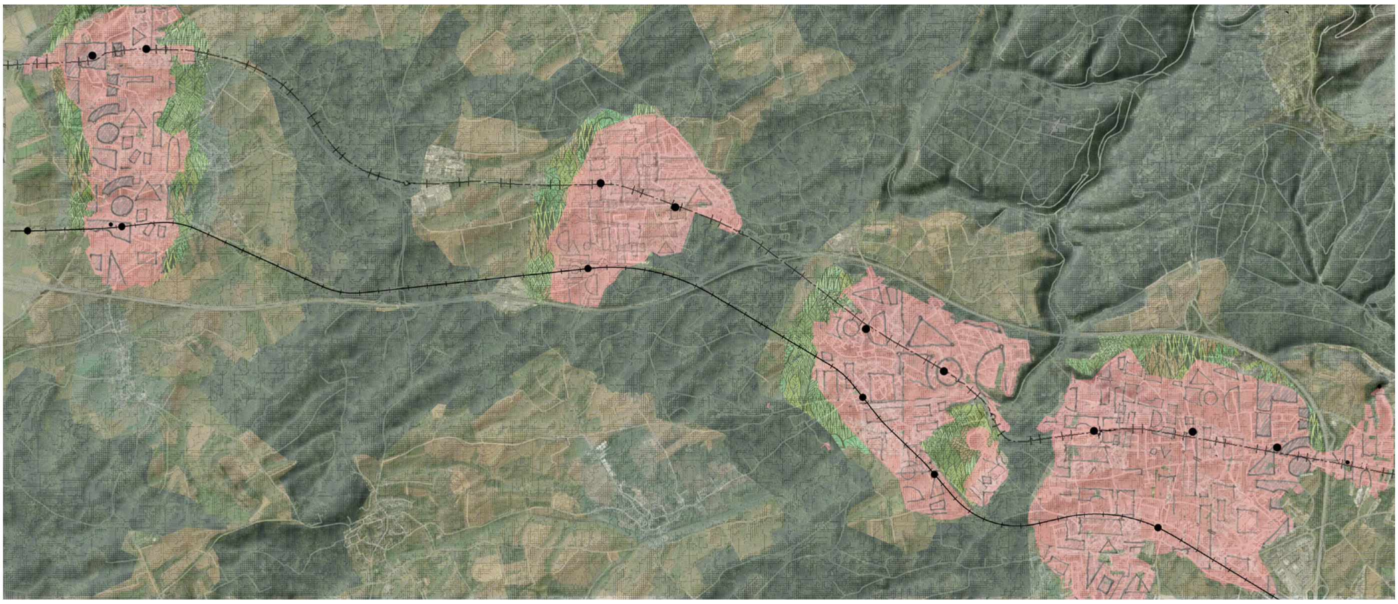
It aims to bring together investigations on land use modelling, with explorations of alternative urban design typologies, linking geospatial analysis with the projective dimension of design.

The goal is to explore spatial configurations for the year 2050 that will be able to accommodate population growth, while reducing the per capita ecological footprint of inhabitants and commuters and sustaining high levels of primary production.

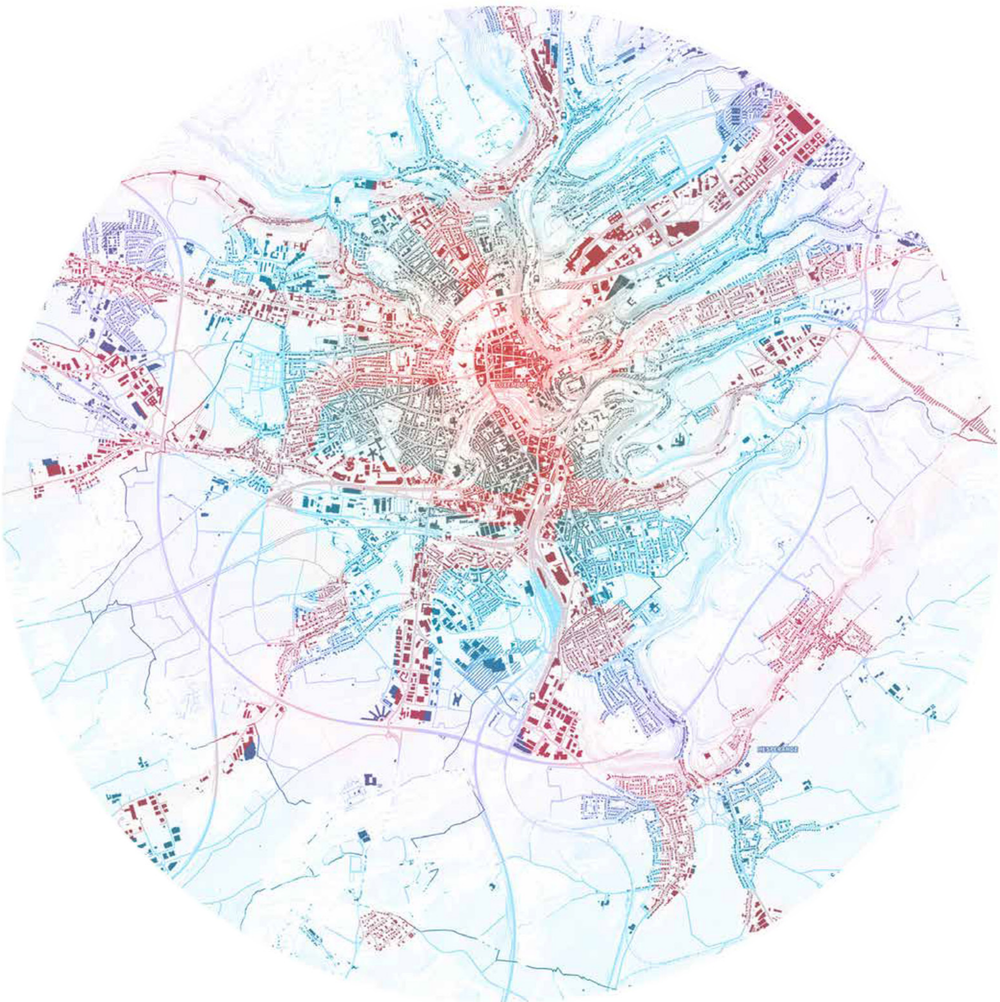
Teaching Team:
Prof. Florian Hertweck, Nikolaos Katsikis, Ivonne Weichold, Peter Swinen

Student Projects

1 LUXEMBOURG RING - Christos Floros, Daniel Domine, Simona Popova
2 A4 CORRIDOR - Raphaela Aurelia Sauer, Vivian Torres, Piotr Pawliszyn
3 WESTERN AXIS - Diana Valentina Zarnescu, Alexandre Lakdar
4 ALZETTE VALLEY NORTH - Andreea-Alexandra Paraschiv, Kalpana Dushyanthi, Piyadigamage, Nazanin Mirsharifi
5 TERRE ROOUGE AXIS - Marina Caroline de Araujo Marins, Soroush Najarsal



3 WESTERN AXIS - Diana Valentina Zarnescu, Alexandre Lakdar

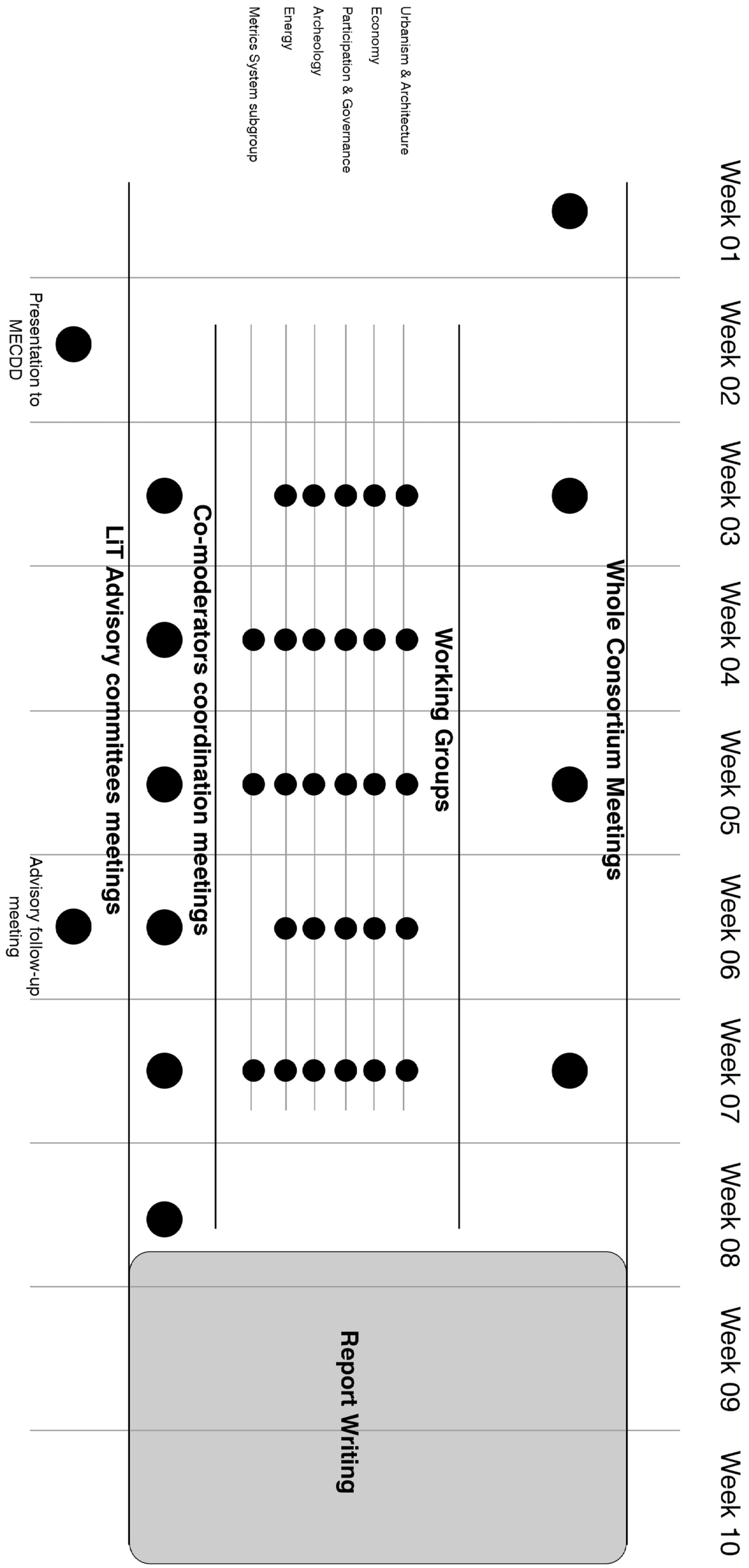


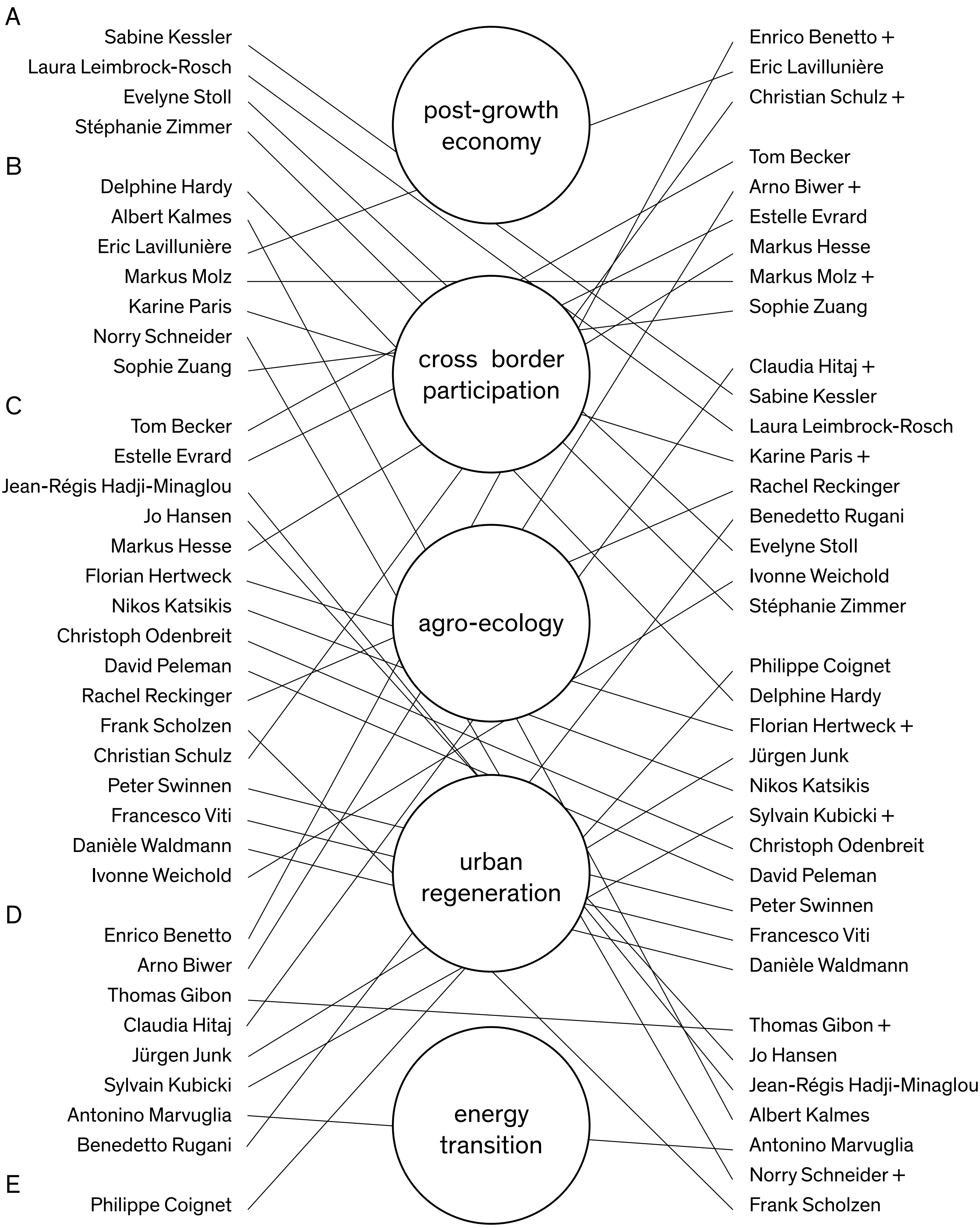
1 LUXEMBOURG RING - Christos Floros, Daniel Domine, Simona Popova

1 LUXEMBOURG RING - Christos Floros, Daniel Domine, Simona Popova

1 LUXEMBOURG RING - Christos Floros, Daniel Domine, Simona Popova

Team agenda of phase 1





Members from 5 institutions [left] have been regrouped into working teams [right]. The + sign next to the name represents the assigned co-moderators of the working groups.

A B C D E

Copyrights iconography

p. 2 fig. 1 © University of Luxembourg / Drawing: Aisha Abdullah
p. 5 fig. 2 © University of Luxembourg / Drawing: Eldin Babic
p. 6 fig. 3 © University of Luxembourg / Drawing: Aisha Abdullah
p. 8 fig. 4 © University of Luxembourg / Drawing: Aisha Abdullah
p. 9 fig. 5 © Florian Hertweck
p. 10 fig. 6 © LUCA Luxembourg Center for Architecture - Stéphanie Laruade, Bohumil Kostohryz, Sophie Langevin, 2015
p. 11 fig. 7 © Tageblatt.lu
p. 15 fig. 8 © University of Luxembourg / Drawing: Nikos Katsikis
p.16 fig. 9 © M3E / MNHA
p. 20 table 1 © LIST / Drawing: Thomas Gibon, Claudia Hitaj
p. 25 fig. 10 © LIST / Drawing: Estelle Tamisier, Thomas Gibon, Claudia Hitaj
p. 26 fig. 11 © LIST / Drawing: Thomas Gibon
p. 27 table 2 © LIST / Drawing: Thomas Gibon, Claudia Hitaj
p. 28 fig. 12 © LIST / Drawing: Thomas Gibon
p. 29 fig. 13 © LIST / Drawing: Thomas Gibon (Data: STATEC, ecoinvent 3.6, myclimate.lu, Carbone4, calculations)
p. 30 fig. 14 © LIST / Drawing: Thomas Gibon (Data: ILR (2020), IEA (2020), and ecoinvent 3.6 database)
p. 33 fig. 15 © LIST / Drawing: Thomas Gibon [Data: STATEC (until 2020), EU Reference Scenario 2011]
p. 34 fig. 16 Source: Photo: Jean Weyrich/LW-Archiv
p. 35 fig. 17 © LIST / Drawing: Thomas Gibon (Data: STATEC until 2020)
p. 36 fig. 18 © LIST / Drawing: Thomas Gibon
p. 37 fig. 19 © LIST / Drawing: Thomas Gibon
p. 39 fig. 20 Source: NECP Luxembourg & Creos Luxembourg
p. 40 fig. 21 Source: Créos
p. 41 fig. 22 © LIST / Drawing: Claudia Hitaj (Data: Sandström et al. (2018), Sala and Castellani (2019)
p. 43 table 3 © IBLA, LIST / Drawing: Evelyne Stoll, Claudia Hitaj
p. 46-48 table 4 © LIST / Drawing: Claudia Hitaj
p. 48 table 5 © LIST / Drawing: Thomas Gibon
p. 49 fig. 23-24 © LIST / Drawing: Thomas Gibon, Claudia Hitaj
p. 53 fig. 25 © LIST / Drawing: Thomas Gibon, Claudia Hitaj
p. 55 fig. 26 © University of Luxembourg / Reckinger, Kapgen & Korjonen (2020)
Drawing: Rachel Reckinger, Diane Kapgen, Helena Korjonen, Sophie Margue (2020)
p. 57 table 6 © LIST / Drawing: Claudia Hitaj
p. 58 fig.27 Source: Fraunhofer ISE (2020)
p. 60 fig. 28 Source: Doick et al. 2014; Monteiro et al. 2016
p. 71 fig. 29 © Peace Advocate Photography
p. 73 fig. 30 © University of Luxembourg / Drawing: Aisha Abdullah
p. 74-81 drawings © Florian Hertweck
p. 81 fig. 31 collage © Florian Hertweck
p. 83 fig. 32-33 © University of Luxembourg / Drawing: Nikos Katsikis
p. 84 fig. 34 © Internationales Bauforum 2019, Jovis Verlag
p. 85 fig.35 © CELL
p. 87 fig. 36 © University of Luxembourg / Drawing: Aisha Abdullah
p. 88 fig. 37 © Googlemaps
p. 103 fig. A1 Source: Junk et al. (2019)
p. 103 fig. A2 © University of Luxembourg / Drawing: Jean-Régis Hadji-Minaglou
p. 104 fig. A3 © LIST / Drawing: Thomas Gibon, Claudia Hitaj
p. 105 - 106 fig. A4 © CELL / Drawing: Norry Schneider