Scaling-up energy sufficiency on a European level through a bottom-up modelling approach: lessons and perspectives

Yves Marignac
Association négaWatt
31–33 rue de la Colonie
FR-75013 Paris
France
yves.marignac@negawatt.org

Stephane Bourgeois, Mathilde Djelali & Nicolas Taillard
Association négaWatt, France

Janis Brizga
Biedrība "Zaļā brīvība"
Latvia

Marta Garcia
Ecoserveis, Spain

Radu Dudau
Energy Policy Group, Romania

Luisa Cordroch
Europa-Universität Flensburg, Germany

Dimitri Lalas
FACET3S, S.A., Greece

Yves Marenne
ICEDD – Institut de Conseil et d'Etudes en Développement Durable, Belgium

Gunnar Boye Olesen
INFORSE-Europe, International network for sustainable energy, Denmark

Philippe Bovet
négaWatt Suisse, Denmark

Yannis Sarafidis
NOA – National Observatory of Athens, Greece

Silvia Erba & Lorenzo Pagliano
Politecnico di Milano, Italy

Léo Coppens
Warocqué School of Business and Economics, University of Mons, Belgium

Benjamin Best & Johannes Thema
Wuppertal Institut für Klima, Umwelt, Energie gGmbH
Germany

Francisco Ferreira
ZERO – Associação sistema terrestre sustentável
Portugal

Keywords

energy sufficiency, modelling, policies and measures, energy services, indicators, co-benefits

Abstract

The unprecedented challenge of reaching carbon neutrality before mid-century and a large share of it within 2030 in order to keep under the 1.5 or 2 °C carbon budgets, requires broad and deep changes in production and consumption patterns which, together with a shift to renewables and reinforced efficiency, need to be addressed through energy sufficiency. However, inadequate representations and obstacles to characterising and identifying sufficiency potentials often lead to an underrepresentation of sufficiency in models, scenarios and policies.

One way to tackle this issue is to work on the development of sufficiency assumptions at a concrete level where various implications such as social consequences, environmental co-benefits, conditions for implementation can be discussed. This approach has been developed as the backbone of a collaborative project, gathering partners in 20 European countries at present, aiming for the integration of harmonised national scenarios into an ambitious net-zero European vision.

The approach combines a qualitative discussion on the role of energy sufficiency in a "systemic" merit order for global sustainability, and a quantitative discussion of the level of sufficiency to be set to contribute to meeting 100 % renewables supply and net-zero emissions goals by 2050 at the latest. The latter is based on the use of a dashboard, which serves as a common descriptive framework for all national scenario trajectories and their comparison, with a view to harmonising and strengthening them through an iterative process.

A set of key sufficiency-related indicators have been selected to be included in the dashboard, while various interrelated infrastructural, economic, environmental, social or legal factors or drivers have been identified and mapped. This paves the way for strengthening assumptions through the elaboration of "sufficiency corridors" defining a convergent, acceptable and sustainable level of energy services in Europe. The process will eventually inform the potential for sufficiency policies through a better identification of leverages, impacts and co-benefits.

Introduction

European governments and the EU have committed to becoming carbon neutral by 2050, and more recently to increase the pathway towards this target through a 55 % cut compared to 1990 levels in 2030. Previous decarbonisation strategies that were set for only 80–95 % greenhouse gas (GHG) emissions reductions at 2050 relied mostly on exploiting energy efficiency and renewable energy for the energy sector (European Commission, 2011; BMWi, 2010). Now, meeting the unprecedented challenge of reaching carbon neutrality by mid-century requires broad and deep changes in production and consumption patterns. Energy sufficiency, as a means to rethink and redesign individual and collective practices to favour activities and services that are intrinsically low on energy use, can be a key further leverage to enable deeper decarbonisation pathways (Marignac, 2019; Zell-Ziegler, 2018). By reducing costs as well as the required size of renewables, storage and their related impacts on materials and land use, it facilitates their achievement. Moreover, a systemic approach encompassing sufficiency (the action on the nature and the level of energy services), efficiency (the action on the performance of energy transformations to meet the resulting demand of services) and renewable energies across sectors enables to address the whole range of environmental, social and societal issues and provide multiple benefits (Thema, 2019; Sovacool, 2020), rather than just climate aspects, in line with a global, ambitious sustainability approach. One of the relevant benefits of including sufficiency is the fact that reducing energy demand at the "origin" contributes to reducing all the material infrastructure for its final use, transmission and distribution, transformation and hence associate material and land use.

At the European level, the sufficiency potential is a hidden resource, but in order to exploit it fully and meet the adequate level of ambition on all sustainability issues, energy demand must be characterised finely and deeply on the level of energy services. This is best to be done at the national level, as there are important differences between European countries, mostly depending on different geographical, economic and political contexts. The European level then enables to compare, and where possible harmonise, reinforce and mutualise those potentials.

Inadequate representations and obstacles to characterising and identifying sufficiency potentials have led to a gap in weighing in sufficiency in models, scenarios and policies (Dufournet, 2019). However, the latest *World Energy Outlook* by the International Energy Agency introduces explicitly sufficiency actions, described there with the term "behaviour changes", and their effect on energy use (IEA, 2020), while the next Advancement Report by the Intergovernmental Panel on Climate Change (IPCC) is expected to contain an entire chapter focused on social aspects that influence energy use and their determinants based on comprehensive recent progress (Creutzig, 2018, 2021; Ivanova, 2020). But sufficiency remains underrepresented in, if not absent from most European energy and climate strategies, whether it is the European long-term vision and the Green Deal (European Commission, 2018, 2019) or the national energy and climate plans, or NECPs (Zell-Ziegler, 2021).

Furthermore, European policy making and scenario modelling has been guided by a top-down rather than a country-based, bottom-up approach. In order to fill this gap, partners of around 20 European countries are working together on the integration of harmonised, sufficiency-based national scenarios into an ambitious net-zero European vision. Among other issues, one of the main areas of focus has been to set the methodological foundations for building sufficiency assumptions, and allowing discussion of various implications such as social consequences, environmental co-benefits and conditions for implementation. To do so, it has to be conducted at the most tangible description level of everyday energy services. The approach is based on a qualitative discussion, setting the role of energy sufficiency in a "systemic" merit order for global sustainability, and a quantitative discussion on the level of sufficiency to be set to aim for this global sustainability. The overall objective is to develop a pathway to meet 100 % renewables energy supply and net-zero greenhouse gas emissions on the European level as soon as possible, and by 2050 at the latest.

Conceptual framework – setting sufficiency within a systemic approach

The growing concern for global sustainability, fuelled by mounting evidence of the ongoing overshoot of planetary boundaries (Rockström, 2009), has progressively led to new discussions (Lade, 2020). Although a faster development of more efficient energy using devices and of greener supply technologies is part of the response, analysis points to the need for deeper changes in societal organisation and practices (Darby, 2018). Sufficiency emerged as a possible concept to "encompass such efforts to rethink and redesign collective and individual practices in line with the Earth limits and people aspirations for better lives", according to a definition coined by the International Network for Sufficiency Research & Policy (Enough, 2018). Nevertheless, sufficiency remains poorly reflected in most of existing ambitious energy and climate scenarios and poorly addressed in existing policies and measures. There is a need, prior to exploring the quantitative role sufficiency can play in building global sustainability, to reflect on the operationalisation of this concept and of the level of priority that it should receive as part of a consistent and ambitious strategy (Toulouse, 2019).

THE PROJECT APPROACH OF THE CONCEPT OF SUFFICIENCY

The concept of 'sufficiency' was introduced in 1993 into the sustainability debate by W. Sachs (1993, 1995):

> A society in balance with nature can in fact only be approximated through a twin-track approach: through both intelligent rationalization of means and prudent moderation of ends. In other words, the "efficiency revolution" remains directionless if not accompanied by a "sufficiency revolution". Nothing is as irrational as rushing with maximum efficiency in the wrong direction.

One operational way to approach energy sufficiency is the notion of energy service, which refers to the services to end-users that are provided through energy chains. Primary energy is converted into final energy delivered to consumers (industries, tertiary consumers, households, individuals), who in turn use technical energy converters to provide them with useful forms of energy (mechanical, thermal, light, etc.), which they use to fulfil services. Shifting to an approach based on energy services, where the whole energy system is considered through the overarching purpose of fulfilling them, leads to shifting from a notion of energy as a simple commodity to a service that has social, ecological and strategic values (Darby, 2018). While the classical approach of efficiency focuses on the performance of equipment, vehicles, heating systems or appliances throughout this energy chain, sufficiency extends to the end-use steps in this chain (Thomas, 2019) e.g. aiming to reduce final service demand (heating/cooling temperatures, floor area, person.km, etc) or adjust technology to provide only the service actually demanded (adequately-sized cars, fridges, correct settings, etc.).

Moreover, a focus on services allows for thinking in terms of "needs", and "wants" (Darby, 2018) in relation to human scale development concepts (Max-Neef, 1991), and to develop reasoning about what it means, e.g. having enough and not using too much. The approach of the overall energy system and its

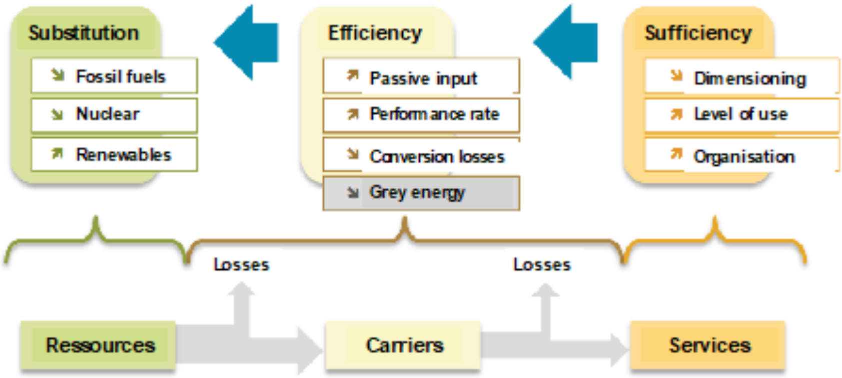


Figure 1. The sufficiency, efficiency and energy substitution approach (négaWatt, 2018a).

sustainability is therefore very much connected to ideas about higher and lower limitations to individual needs deriving from the "doughnut economy" concept (Raworth, 2017; Spengler, 2016). According to this approach, the "safe and just space for humanity" has to be set between two boundaries: the lower one, or "social foundation", corresponds to the satisfaction of all basic individual needs for all (of which energy ones), whereas the upper one, or "environmental ceiling", corresponds to the limitation of global impacts (of which climate change) through keeping mean individual consumption at a certain level (Raworth, 2012). This approach can be applied to define the notion of "sufficient energy service" (Darby, 2018), encompassing the main areas of individual welfare where access to energy services is crucial (shelter, mobility, health …) on the lower side, and the main global environmental concerns that are at least partly energy impacted (climate change, air pollution, erosion of biodiversity, land and water availability, use of materials, etc.) on the upper side.

Lower use of energy and materials though should not be confused with lower welfare levels, nor with restriction or deprivation, (Jackson, 2017). Research shows that the growth in use of energy and materials has in many countries reached levels where this use becomes dysfunctional and harmful to general and individual welfare (Douglas, 2011; Brown, 2016; Burke, 2020) due to its impacts on e.g. "physical inactivity, obesity, death and injury from crashes, cardio- respiratory disease from air pollution, noise, community severance and climate change".

SUFFICIENCY AS PART OF A SUSTAINABILITY ORDER METHODOLOGY AIMED FOR ACHIEVING GLOBAL SUSTAINABILITY

One key issue for integrating sufficiency in global strategies aiming for long-term sustainability is the way it interacts with other options such as the more traditional energy efficiency technologies and substitution between energy resources ("consistency"), in terms of how the model describes the energy system and how it accounts for changes in that system. Thinking of the whole energy system as a means for an appropriate delivery of energy services leads to a consideration of energy sufficiency as the first logical step to reduce final use and hence the size of infrastructure for energy generation, transformation and transport with its embedded energy, land use, and operational losses and therefore reduce "at the origin" the overall impacts of the energy system. This approach, as illustrated in Figure 1, contrasts with the more traditional approach where on the contrary sufficiency is considered as an additional option that needs to be activated once some limits of the potential for efficiency and decarbonised energy supply seem to have been reached.

A consistent combination of sustainability options through time, depending on their interrelated impacts, requires further refinement of the approach. There is a need to take into account not only the intrinsic merits of the different options regarding sustainability but also their possible level of implementation, together with the relationship between impacts and implementation conditions. This approach helps to build a relative order of preference, which needs to be discussed and adjusted in different contexts.

Regarding sustainability, the IPCC recently proposed a global review of the assessment studies of various options for reducing net GHG emissions, responding to climate action, the 13th of the 17 social, environmental and economic Sustainable development goals (SDG) established by the United Nations, in respect to their contribution to the 16 others (IPCC, 2018, chapter 5). For each of the 23 options considered, the IPCC provides a score between -2 and +3 (sometimes with a range) which characterises the expected impact of the corresponding action on each of the SDGs, when it is characterised through scientific literature[1]; the scores attributed by IPCC through this comprehensive review are summarised in Table 1. The cumulative score (unweighted aggregate) of each option over the 17 goals has been calculated by the négaWatt association so as to provide an indication regarding the global performance of each option considered. This analysis, although subject to uncertainties, provides a strong indication that options for the reduction of GHG emissions are likely to have various systemic impacts on the whole set of sustainability objectives, with a various sensitivity to their conditions of implementation. This approach could serve as a basis to reflect on a systemic sustainability ranking. Together with improved energy efficiency, the "behavioural response" as considered by IPCC (as a category e.g. in buildings or transport), which is more related to sufficiency, show a positive impact on a large number of SDGs, with no or little negative impacts on some, and a very low variation of the expected impacts, showing a low dependency on the context and conditions of

1. The IPCC further provides indications about the level of evidence, agreement and confidence found in scientific literature on each of the issues.

implementation, which puts them fairly high in such a priority ranking.

The relative scalability of various transformation options is another important issue to consider, taking into account the range of geographical expansion, the pace of economic penetration and the time scale of implementation. The *availability* of options, e.g. their technological readiness level (TRL) and their industrial readiness level (IRL), has first to be considered, keeping in mind that their impacts should also be managed, which is dealt with through the introduction of an innovative environmental and social readiness level (ESRL) based on the state of characterisation, assessment and projected acceptability of the impacts (négaWatt, 2018a). The *affordability*, or the economic access of different players and people to those options in different places, also needs to be taken into account. The *granularity* of implementation is another key criteria, as more-granular options are likely to accelerate overarching transformations (Wilson, 2020). The analysis shows that many sufficiency options rank high regarding these criteria, which makes them some of the most scalable options in the global portfolio. Moreover, a clear benefit from implementing sufficiency is that it might in turn reinforce, through its impact on the size and dynamic of the systems, the potential for scaling up other considered options. Furthermore, the need of achieving reductions of emissions extremely rapidly, within 2030, in order to remain within the 1.5 °C or 2 °C carbon budget (Jackson, 2019) is a strong reason to include sufficiency since at least part of the sufficiency enabling infrastructures are low cost and can be implemented rapidly.

Finally, in the context of a perceived growing exposure of our society to various shocks, exacerbated by the Covid-19 crisis, further attention is brought on the respective robustness of the options for positive transformation, and their contribution to a form of resilience. From that perspective also, preliminary analysis developed for the project points to a positive contribution of sufficiency, as it can reduce the source of some of the risks to be considered, the vulnerabilities of economic and social structures to some of the possible shocks, and the residual impacts arising from such shocks.

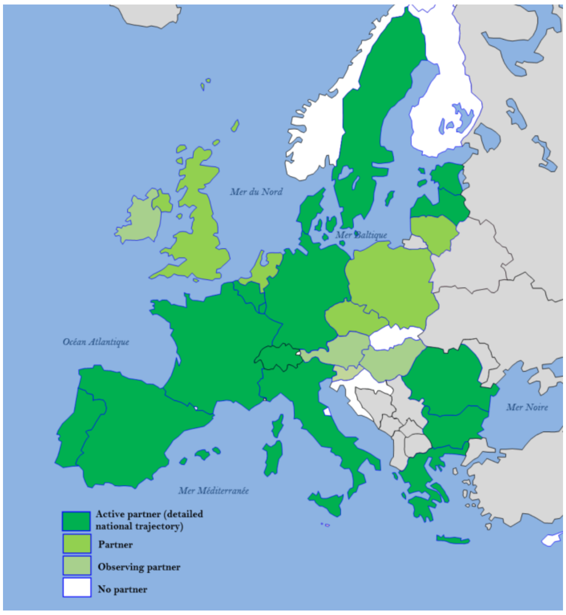
Operational framework – addressing sufficiency through a technical dialogue

Sufficiency options, and the way they can be implemented, combined with policies fostering efficiency and renewable energies, are very much dependent on energy consumption patterns which, in turn, are context-dependent, whether it is from a geographical, economic or social perspective. Although sufficiency could be considered as a global leverage on the European level, the discussion of its role as part of a comprehensive

Table 1. Relative impact of greenhouse gas emissions mitigation options on Sustainable Development Goals.

Options for climate action (reduction of net GHG emissions) \ United Nations sustainable development goals		Social				Social 2				Environmental				Economic					Cumulative score		
		1	2	3	4	5	10	16	17	6	12	14	15	7	8	9	11	13			
		No Poverty	Zero hunger	Good health and well-being	Quality education	Gender equality	Reduced inequalities	Peace, justice and strong institutions	Partnerships for the goals	Clean water and sanitation	Responsable consumption / production	Life below water	Life on land	Affordable and clean energy	Decent work and economic growth	Industry, innovation and infrastructure	Substainable cities and communities	Climate action	Maximum	Total (mean value)	Minimum
Industry	Accelerating energy efficiency improvement	+2		+2	+1		+1		+2	+2 -1	+1			+2	+1	+1	+2	n.d.	17	15,5	14
	Low-carbon fuel switch			+2	+1				+2	+2 -2	+2		+1 -1	+2	+2	+2	+2	n.d.	18	15	12
	Decarbonisation/CCS/CCU			-1					+2	+1 -1	+2	-1		+2 -2	+2	+2		n.d.	9	6	3
Buildings	Behaviorial response	+2		+2				+2		+2	+2			+2	+2	+2	+2	n.d.	18	18	18
	Accelerating energy efficiency improvement	+2 -1	+2	+2	+2	+1	+1 -1	+2	+2	+2	+1		+2	+2	+2 -1	+2	+2	n.d.	27	23	19
	Improved access & fuel switch to modern low-carbon energy	+2	0 -1	+2	+1	+1		+2	+2	+2 -1	+2 -1		+2	+2	+2	+2	+3	n.d.	25	21,5	18
Transport	Behavioural response	+2 -1	+2	+2 -1	+1	+1	+2	+1 -1	+2	+2	+2			+2	-2	+2 -2	+2	n.d.	21	15	9
	Accelerating energy efficiency improvement	+2 -1		+2				+2	+2	+2	+2			+2	+2 -2	+2 -2	+2	n.d.	20	14,5	9
	Improved access & fuel switch to modern low-carbon energy	+2 -1	0	+2			+2	+1 -1	+2	+2 -1	+2			+2	+2 -2	+2	+2	n.d.	21	15	9
Replacing coal	Non-biomass renewables	+2		+2	+1	+1	+1	+2	+2 0	+2 -2	+2	+2 -1	-1	+3	0	0 -1	+2	n.d.	21	16	11
	Increased use of biomass	+2 -2	+2 -2	+2						+1 -2	+2		+1 -2	+3	+1	+1		n.d.	15	8	1
	Nuclear/Advanced Nuclear			-1				-1		+2 -1			-1	+1	+1	-1		n.d.	0	-1,5	-3
	CCS: Bio energy	+2 -2	+1 -2	+2 -1						+1 -2	+1		+1 -2	+2	+1	+1		n.d.	12	4	-4
Advanced coal	CCS: Fossil			-1						+1 -2				+2	-1	+1		n.d.	2	0,5	-1
Agriculture & livestock	Sustainable healthy diets and reduced food waste	0 -1	+2	+1				+1 -1	+1 -1	+2 -1	+2		+1	+1	+1	+1		n.d.	13	9	5
	Land based GHG reduction and soil carbon sequestration	+2	+2	+2 -2	+2 -2	+2 0	+1 0	0 -1	+2	+1 -1	+1		+1 -1	+1	+2 -1	+2 -2		n.d.	21	9,5	-2
	Improved livestock production and manure management systems	+2	+2	+2 -2		+2 0	+1 0	+1	+2	+2 -1	+1		+1	+1	+1	+2		n.d.	20	15	10
Forest	Reduced deforestation, REDD+	+2	+1 -2		+1	+1 -1	+2	+2	+1 -1	+1 -1	+1		+1	+1 -1	+1	+1 -1		n.d.	16	9,5	3
	Afforestation and reforestation	+2 -2	+1 -1	+1	-1	+1	+1	+1	+2	+2 -1		+2	+2	+1	+2		+2	n.d.	18	14	10
	Behavioural responsible sourcing					0	0	+1	+1	+2 -1	+1		+1 -1	+1	+2	+2	+2	n.d.	13	10,5	8
Oceans	Ocean iron fertilization		+1 -1									+1 -2						n.d.	2	-0,5	-3
	Blue carbon	+3	+3							+2		+2 0	+3					n.d.	13	12	11
	Enhanced Weathering											+2 -1	-1					n.d.	1	-0,5	-2

Source: négaWatt, from (IPCC, 2018).



BE	ICEDD; Sebastien Meyer
BG	Za Zemiata; Sofena
CH	NégaWatt Suisse
CZ	Charles University Environment Centre
DE	Wuppertal Institut; Univ. of Flensburg; Fraunhofer ISI
DK	INFORSE Europe
EE	Tallinn Technical University (Taltech)
ES	Ecoserveis Association
FR	NégaWatt Association
EL	National Observatory of Athens (NOA)
IT	EURAC Research; Politecnico di Milano
LT	Lithuanian Energy Institute (LEI)
LU	Consortium Cell/List
LV	Green Liberty - Zala Briviba
NL	Quintel
PL	WiseEuropa
PT	ZERO
RO	Energy Policy Group (EPG)
SE	Air Clim Coalition
UK	Center for Alternative Technologies (CAT)

Figure 2. The partners network European sufficiency-based scenario project.

and meaningful strategy makes more sense on a level which allows for taking national contexts into account. The idea to complement existing top-down visions built on the European level, with a bottom-up approach starting on a country level led to the building of a specific network and dedicated tools.

BUILDING A DEDICATED PARTNERS NETWORK WITH A SHARED COMMITMENT TO SUFFICIENCY AS A KEY SUSTAINABILITY LEVERAGE

A network of 23 organisations from 20 European countries (including 18 EU Member States, plus the UK and Switzerland as detailed in Figure 2)[2] are involved in a technical dialogue around the creation of a common vision. While most have developed energy and climate scenarios for their national countries or regions, sometimes for official exercises such as Nationally Determined Contributions (NDCs) under the Paris Agreement or National Energy and Climate Plans (NECPs), the recency of their work, the modelling tools they use, the level of detail and attention to sufficiency differ widely, with some partners more focused on policy analysis and advocacy. All partners from research institutes, technical universities, think tanks, consultancies and NGOs, are committed to developing a mutual understanding and setting ground for common work on the construction of an ambitious European vision, based on national trajectories with a strong sufficiency focus that enables a soon and realistic zero emissions scenario. Their size, their institutional role and modelling capacity, their relationship to public institutions and public strategies is very diverse; from technical dialogue and research to public advocacy, a wide range of implication levels allows to move forward with this work addressing a large number of issues. A dozen national partners are actively working on the completion of a national, sufficiency-based trajectory, a few others take an active part in the technical exchange without working on their own trajectory. Further, observing partners are consulted around normalised trajectories for their national countries, and some will be involved at a later stage in the policy and dissemination activities.

The diversity of the actors and national contexts helps to enrich the exchange. Through the dialogue, partners are invited to share information and best practices on energy modelling and scenario building with a view to setting climate and energy policy agendas, as well as on the integration of energy sufficiency in this process. Their work and modelling approaches are compared, questioned, and can be mutually reinforced. Collective understanding of energy sufficiency is deepened, and capacities are strengthened throughout the network. Eventually, by fostering mutual benefits, the process is a means to raise the ambition and deepen national partners' modelling approaches and accounting of sustainability, and sufficiency in particular.

BUILDING THE REQUIRED TOOLS AND PROCESSES FOR A BOTTOM-UP SCENARIO BUILDING

The innovative nature of the implemented approach required to develop specific methodological steps and tools. The objective was to enable the building of an integrated trajectory, on the European level, based on harmonised national trajectories which need to be elaborated in a consistent way for each country, taking into account the discrepancies in the level of detail and scope of available data, or the models used to develop existing scenarios that could serve as a reference or a basis.

A three-stage bottom-up integrating approach

The first need was to design a process to elaborate a European vision on the basis of national trajectories as modelled by partners, while guaranteeing the consistency of the prospective analysis through the projected reinforcement and harmonisation work. This specific bottom-up construct, contrasting with most ambitious European scenarios that are built at the aggregated European level, relies on an iterative process illustrated in Figure 3, based on three stages:

2. The project is developed on a coherent geographical area that encompasses the EU plus UK, which was still part of it when the project started, Switzerland and Norway.

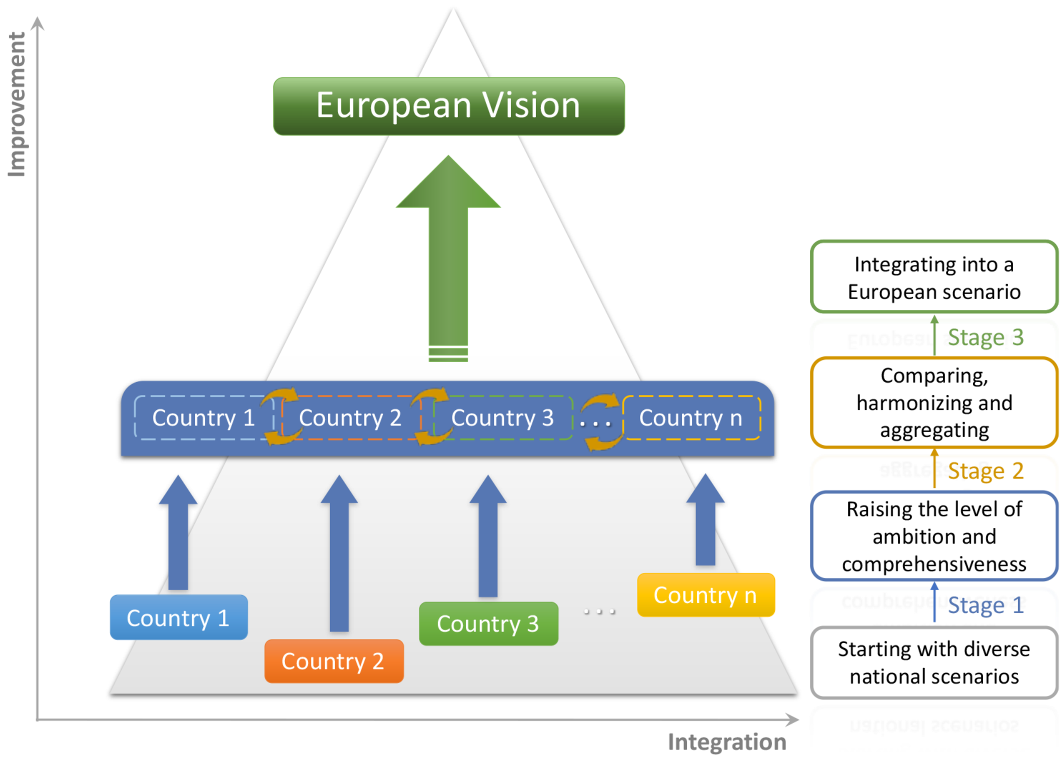


Figure 3. The three-stage bottom-up approach to building a European vision.

- Stage 1: to start with, national trajectories are collected and discussed, through the use of a common descriptive dashboard enabling for their comparison; the objective is to identify areas of improvement to reinforce their average level of ambition and comprehensiveness;
- Stage 2: the national trajectories will then be aggregated to form a European one, which will inform the need for consistency and reinforcement of the trajectories and lead to further harmonisation and improvement;
- Stage 3: the reinforced aggregated national trajectories will nevertheless remain mostly juxtaposed, so the last step will consist in further integrating them into a coherent European vision. This will be achieved through a simple modelling approach, addressing for instance the mutualisation of efforts and potentials between countries to search for some optimisation of the trajectories.

A simple and robust modelling tool

There are examples of models designed to develop such an aggregation and integration of energy systems on different geographical scales. The lack of homogenous and detailed data and the various modelling challenges arising from their articulation are some of the main identified obstacles. To remove these barriers, a tool has been adapted from négaWatt's PRES model (négaWatt, 2020), which had been designed both to build trajectories at the scale of a given French region, by crossing final energy needs with the energy sources required to meet them, and then to aggregate the regional trajectories thus obtained at the national level.

Using input data on final energy consumption by sector and by family of energy carriers and prospective assumptions on energy supply by sector, PRES models in a simplified way the main transformations between energy carriers as well as the losses in the transport and distribution networks (see Figure 4). The model carries out energy balances by comparing production and consumption (encompassing final energy consumption and internal uses, i.e. conversion to other energy carriers) and an equilibrium has to be met for each energy carrier, and each energy network (power, gas, heat…). Regional energy sources are mobilised as a priority, and a balancing by using imports or exports can be applied if necessary, to fill the gap between supply and demand. As a first approximation, the model does not address the issues of hourly supply and demand balance, which requires too fine a modelling of demand and production compared to the available data. It is therefore a net balance of imports/exports over a one-year period. The resources considered are either primary resources, or secondary resources derived from them after a first transformation: thus, the liquid biomass taken into account corresponds to the local production of agrofuels, and is therefore not strictly speaking the primary biomass from which they are derived. In the same way, biogas corresponds to the net production at the exit of the digesters and not strictly speaking to the primary biomass from which it is derived. These accounting choices were determined in particular by the quantities usually available in statistics. The model calculates the Primary Energy Factors (PEFs), as per existing recommendations[3]. Three PEFs (renewable, non-renewable and total) are calculated for each of the following energy carriers: electricity, liquid fuels, hydrogen, methane and

3. Energy performance of buildings – Determination and reporting of Primary Energy Factors (PEF) and CO_2 emission coefficient – General Principles, Module M1–7. See http://www.euroheat.org/wp-content/uploads/bpfb/tmp/tc_371_wi_371007_e.pdf.

Figure 4. Overview table of energy transformations modelled in the négaWatt's PRES model.

heat from networks. They are calculated for the regional energy system as a whole (not specifically for a given sector, such as building/residential sectors). Following the same guidelines, transmission and distribution losses are taken into account.

The tool adapted from PRES is a simple simulation model, implemented with Excel and calculating incremental changes on a chosen time step (which is set to 5 years in the project). As shown in Figure 5, it consists of different spreadsheets that communicate with each other:

- A national calculation model (adapted from the négaWatt's PRES model) that carries out energy balances for each country by cross-referencing consumption and production data and calculates the following output indicators for each time step: reduction of fossil primary energy consumption, achievement of the target for reducing final energy consumption in 2030, share of RES in gross final consumption (all sources or domestic production only), share of RES exports, RES share in final electricity/motor fuels/methane/heat consumption, nuclear share in electricity production, energy independence rate, reduction of GHG emissions (CO_2 emissions) compared to 1990, total net GHG emissions, primary energy factors, share of non controllable energies
- A data entry file for each country, which will feed the national model. This data entry file retrieves its values from the demand calculation module, which calculates the final energy demand with the data from a harmonised dashboard, taking into account changes in consumption both through efficiency (e.g. energy performance of heating systems) and sufficiency leverages (e.g. rate of equipment ownership of tumble dryers) (related to possible actions and programmes), the prospective assumptions specific to each demand driver being constructed exogenously to the model;
- A European synthesis module (adapted from the négaWatt's PRES model), which aggregates the results of the calculations carried out in the national module. This module applies the same formulas for calculating output indicators on the cumulated energy balance, in order to be able to compare them with the European objectives (for indicators for which a target is defined in official documents).

A common descriptive indicators dashboard

The chosen bottom-up approach implies that the initial national trajectories can be based on different methodologies, models, cover different scopes and rely on various logic and level of aggregation or disaggregation of data. However, the comparison, harmonisation, reinforcement and integration process require that these trajectories use a "common language". The need to compare heterogeneous trajectories has led other projects to reflect on descriptive tools: in France, the group of experts that was set up during the national debate on energy transition, in 2012–2013, relied on this approach to compare more than 25 existing scenarios and trajectories (Grandjean, 2014); on the international level, the Deep decarbonisation pathway project (DDPP) has developed the concept of a common dashboard to compare existing trajectories within a country or between countries (Williams, 2017).

A dedicated indicators dashboard was therefore developed to "translate" different trajectories in a common, sufficiency-focused, language and provide a homogenous description of national trajectories, both to support their comparison and serve as an interface for the modelling process. The dashboard therefore serves as a common framework, firstly because it establishes the set of indicators that must be addressed in all national trajectories (up to around 600 in total, e.g. the final consumption of transports, its breakdown by mode, the average efficiency of cars per engine type, the number of km per person per mode per year, etc.). All indicators included in the dashboard underline the energy system and are ranged by sectors, energy uses and potentials and have been discussed and selected for characterising demand in a way that allows for addressing sufficiency options. The common framework is also provided by the logical structure of the dashboard, which con-

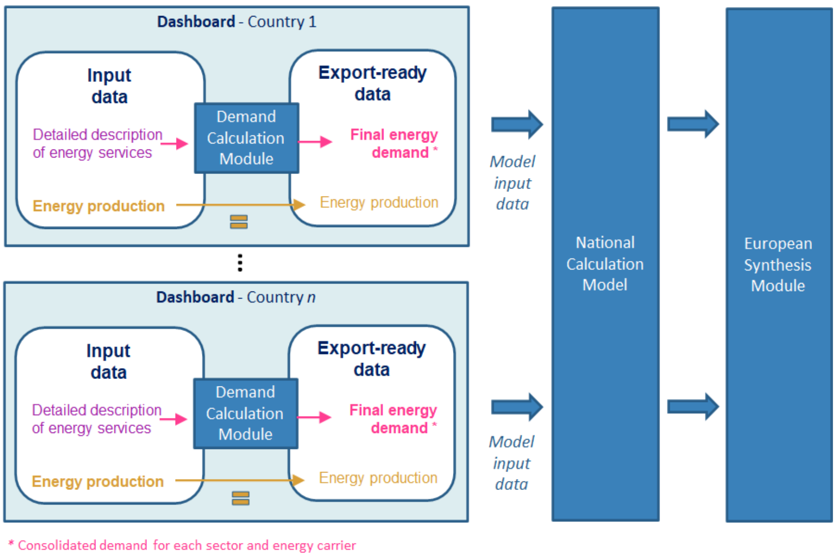


Figure 5. The modelling approach.

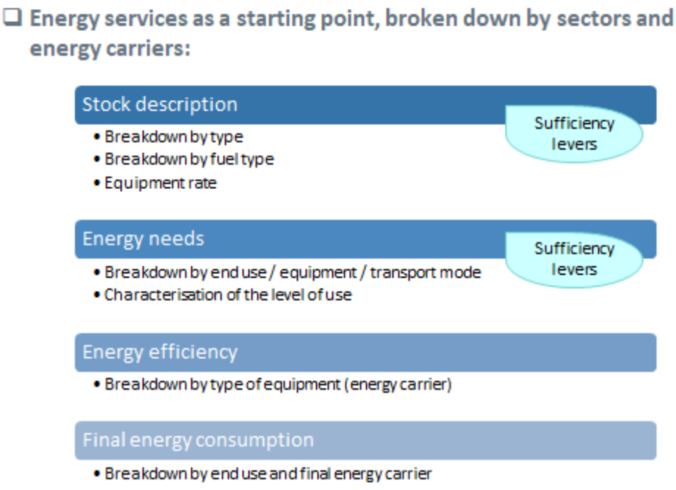


Figure 6. The indicators dashboard organisation and logic (example of the transport sector).

sists in starting with a descriptive characterisation of energy demand in terms of stocks, energy services and needs before getting into energy efficiency rates to be applied for different energy carriers and then into final energy consumption, broken down by end use and final energy carrier, as illustrated in Figure 6 in the transport sector.

Throughout the technical dialogue, a balance was found in the level of detail of the dashboard to enable an accurate enough description of energy services demand, while remaining accessible to those partners lacking part of the data. As the sectors covered and the level of detail available may considerably vary between countries, a pragmatic approach was taken, using a sort of "Russian dolls" system, for indicators per sector, with detailed indicators where those are available, or more aggregated indicators otherwise. The structure was also developed using available indicators from Eurostat and Odyssee data bases to ensure that all trajectories are based on a consistent and comparable starting point.

Prospective work – building sufficiency-based pathway(s)

Specific focus is set through this approach on the primary role of energy sufficiency – in line with the sustainability approach. Selected sufficiency-related indicators feed a discussion on the possible evolution of energy services, leading to the introduction of sufficiency-based corridors to refine trajectories.

THE WORK ON SUFFICIENCY-RELATED INDICATORS AND THEIR RELATIONSHIPS

A first, key building block on the construction of a common sufficiency modelling language has been the work on sufficiency indicators. Working groups have been created for the transport and buildings sectors for key experts from partner organisations to define and prioritise a list of sufficiency indicators. Sufficiency indicators and drivers were collected and characterised in categories (e.g. relating to public infrastructures, such as "square meters of green spaces per inhabitants", demographics, building stock description, level of needs, description of needs, etc.). Through the technical dialogue, criteria were set to categorise and prioritise key indicators for the scenario building, namely:

- Quantitative indicators were distinguished from qualitative indicators, which cannot be easily quantified (e.g. "safe bike parking facilities"). Those categories were then fine-tuned according to the availability of data throughout Europe;
- The interrelations between sufficiency-related indicators were explored, through an indicative mapping of causal chains, such as that illustrated in Figure 7 where different indicators interrelated to the key or aggregate indicator for the building sector of per capita heated and conditioned surface (m^2) are identified. This is helping a better shared understanding of how the various relevant indicators can be mobilised as contributing factors to the evolution of energy services;
- These interrelations were themselves characterised according to their nature with regards to scenario building, as an easily quantifiable function, more difficult to quantify, or not quantifiable.

As such, this enabled further fine-tuning of creation of a priority order of indicators with a view to their integration in scenario modelling: while some drivers will be kept for the construction of a narrative and are being used to develop assumptions for other, more quantitative indicators, 10 quantitative indicators for transport were adopted and integrated in the dashboard (as summarised in Table 2), and 14 indicators for buildings.

The work on sufficiency-related indicators, which was developed in the limited framework of the project is still exploratory and seems worth being pursued. It is being deepened in the framework of the CACTUS project ("Consolidating Ambitious Climate targets Through end-Use Sufficiency"), involving four of the partners around the integration of sufficiency in climate and energy strategies in Central and Eastern Europe, with Hungary and Lithuania as focus countries. Causal links between indicators have been detailed and a technical dialogue on the construction of assumptions in the specific context of "catching-up economies" is being implemented: issues such as the specific energy sufficiency potential and the definition of sufficient levels, taking into account lower levels of energy ser-

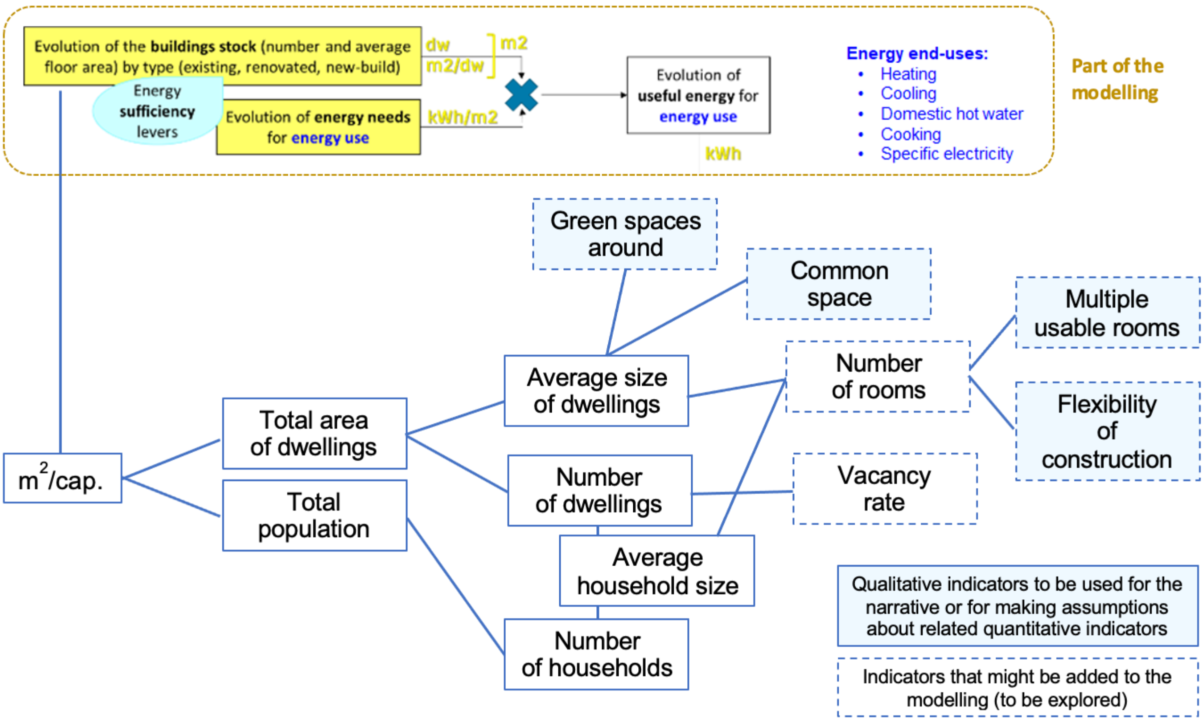


Figure 7. An illustrative mapping of causal chains for sufficiency indicators for the buildings sector.

vices request and high energy poverty rates are being explored. This work will be implemented with a link to the convergence and contraction approach to be addressed in the following chapter. The latter will also deepen current partners' exchanges on the construction of sufficiency assumptions, their comparison, with a view to their harmonisation and the reinforcement of national trajectories.

COMPARISON OF NATIONAL TRAJECTORIES AND BUILDING OF SERVICE-BASED SUFFICIENCY CORRIDORS, TAKING INTO ACCOUNT NATIONAL SITUATIONS AND SPECIFICITIES

Once sufficiency-related indicators have been selected and discussed, they can be used to further inform the integration of sufficiency in the construction and reinforcement of trajectories.

Convergence in the buildings and transport sectors

While the technical dialogue helped to define the sufficiency indicators relevant for the construction of energy transition scenarios and informed how to build assumptions on them, applying this to actual trajectories is not straightforward.

The data needed to characterise these indicators are not uniformly available in all the countries under consideration, either in historical databases or in prospective exercises. For example:

- regarding historical data, soft modes are often absent (total passenger-kilometers or modal share) from the statistics or available in the case of pilot projects and for a restricted perimeter (e.g. limited to urban trips in a few countries)[4];
- regarding prospective data, some effects specifically related to sufficiency leverages are sometimes accounted for through efficiency indicators. For example, only one efficiency indicator for passenger cars is generally available, whereas the weight of vehicles (to name only one) is also a determining factor in vehicle consumption. Similarly, in housing, indicators for space heating are generally only partially available (e.g. from the energy certificate or via measurement).

The example of heating in buildings illustrates the type of analysis that is eventually needed. Indicators might be available in terms of "energy needs" or "delivered energy"[5]. "Energy needs" may be influenced both by the technical features of the building fabric and ventilation system and by sufficiency practices of the occupants (Sfakianaki, 2011, Salvia 2020). Similarly "delivered energy" which is required by the active heat generation systems (e.g. a boiler or heat pump) in order to supply the required "energy needs" to conditioned spaces, will depend on the latter drivers, plus the technical efficiency of the generation plant and the distribution and diffusion elements (Pagliano, 2019). As per the evolution over time of certain indicators, one should also consider the effect of changing climate and the possibility to estimate those effects at the regional and local scale using adequate weather files (Erba, 2017). For example both "energy needs for heating and cooling" and "delivered energy" will be influenced in terms of available efficiency and sufficiency options and their impact by the evolution of winter and summer temperatures in the environment surrounding buildings depending on the progression of global and local warming (Erba, 2019).

4. They are, for instance, not included in the Eurostat data, that serve as one of the main basis for the project, apart from a specific mobility survey covering 12 Member states (Eurostat, 2021).

5. We adhere here, and throughout the project to the Terms and Definitions set up in European and International Standards, e.g. EN-ISO 52 000 for the energy performance of buildings: They can be found within the individual Standards and on the Online Browsing Platform (OBP) of ISO at https://www.iso.org/obp/ui/#search.

Table 2. Prioritisation of sufficiency indicators for scenario modelling in the transports sector.

Type	Indicator	Unit	Adopt	Explore	Major difficulty	Narrative	Not explored	Available data on European level
Social drivers	Symbolic order	–		■				–
	Gender bias	–		?		?		–
	Violence	–					■	–
Legislative framework/ legal drivers	Regulation imposing bike places (in buildings/cities)	–		■				–
	Company cars	nb.		■				No
	Tax break for commuting	%		■				–
Infrastructures	Bike paths	km		■				No data
	Seamless cycle network	–			■			–
	Speed limit (share by category)	km/h			■			Yes/No
	Public space given to non motorized transport	–			■			–
	Space allocated to car-parking (and bike-parking)	nb.			■			–
	Density of urban/rural areas	Pers./m²		■				Eurostat
	Public transport per person	km/pers.		■				–
	Proportion of children able to go to school without car	%			■			–
Equipment/ level of use	People per vehicle (average)	nb.	■					No
	Load factor for freight	%	■					No
	Nb of cars/vehicles per person	nb./pers.	■					Stock of veh.
	Rate of private car ownership	%	■					No
Description of needs	Total mobility of passengers and freight disaggregated by type, mode …	pers.km t.km	■					Yes but variable level of detail
	Average number of trips	trips/ pers/day		■				–
	Level of telework	days/ pers/year			■			No
	Share of commutes removed by telework	%		■				No
	Distance travelled from home to work (by mode, etc.)	km		■				Average length by car
	Share of non-motorized mobility	% of km	■					No
	Share by electric bike	% p.km	■					No
Energy efficiency	Indicator of performance (break by mode, etc.)	tep/km	■					–
	Average vehicle weight/size	kg		■				Nr of cars per weight
Final	Final energy consumption	tep	■					Yes

The description of the trajectories through the common dashboard is therefore adjusted at first, for each trajectory and in each sector, to the level of detail that corresponds to the available data. It could then be extended to a further level of detail through the introduction of more disaggregated assumptions, separating the factors of change corresponding to a given aggregated indicator: for instance, an aggregated data about passenger-kilometers could be split between modes, introducing assumptions to reflect the current situation and allowing for discussions about its possible evolution through modal shift. The purpose is not to develop the same level of detail for each part of the dashboard, but to focus on areas and indicators that are considered the most important regarding the quantification or the consistency of trajectories.

Further processing of data is also needed to take into account the variations of definitions or perimeters from one country to another (e.g. whether for traffic or for final energy use, light utility vehicles can be included in passenger or freight transport depending on the reporting country). Some indicators also need to be normalised to allow a direct comparison between countries (e.g. consumption must be divided by the population or by the number of households).

Such processing of the data gathered through the dashboard eventually allows for applying a contraction and convergence approach to energy consumption through dedicated comparison indicators relating to the level of energy services. This approach has been documented, for instance, through the calculation of convergence and contraction factors in the EUCalc project (Climact, 2019). A similar methodology was developed here to introduce proposals of sufficiency corridors, as a basis for further discussion. This was for example used to discuss two key sufficiency-related indicators, which are usually well-detailed in prospective exercises, as they are essential for assessing consumption in many approaches:

- residential floor area (m^2/cap.): useful floor space of dwellings permanently occupied divided by the population;
- passenger traffic (pkm/cap.): number of passenger-kilometres travelled per person and per year within the national territory (excluding aviation and LDV; including non-motorised mode).

These two indicators are based on population and its projected evolution up to 2050. This choice implicitly reflects a search for convergence in living standards. This orientation, in line with European policies such as the European Pillar of Social Rights (European Commission, 2021), is seen as a leverage to reduce inequalities and to integrate social justice values into the prospective exercises. However, it may tend to ignore certain constraints linked to lifestyle (harsher climate implying more time indoors and therefore a greater need for space, larger share of rural population implying different mobility needs, etc) or starting conditions (existing housing stock complex to reorganise, state of public transport infrastructure, etc.) making it more complex to harmonise sufficiency objectives.

A fairly strong standardisation of efficiency targets is relatively simple, based on best practices (e.g. renovation depth), best available techniques (e.g. heating systems) and EU legislation, which is well developed in this field, provided that the time required to renew the stock (vehicles, buildings, heating appliances) is taken into account and that certain indicators are standardised to take into account national specificities (climate conditions, energy mix). Concerning sufficiency indicators, it is very difficult to obtain a similar value for all countries. For instance, among partners' initial trajectories, hypotheses on floor area and passenger traffic varied respectively between plus and minus 30 % and plus and minus 20 % respectively (see Figures 8 and 9). A certain room for manoeuvre allowing enough accounting of national specificities may therefore be beneficial. It will be applied through "sufficiency corridors" around target

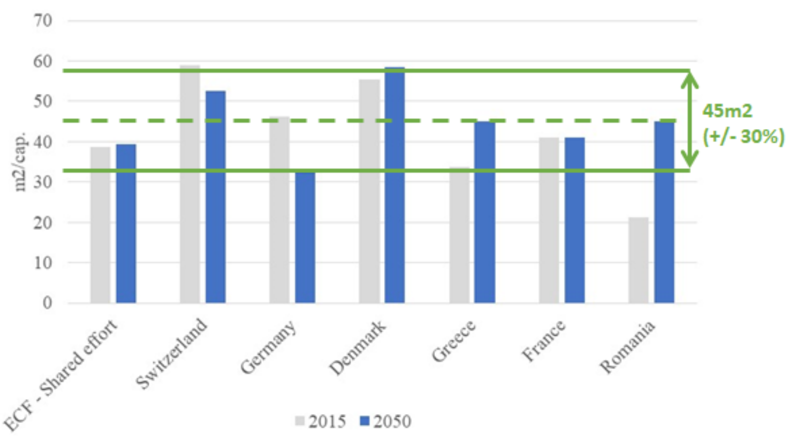


Figure 8. Illustration of the differences of sufficiency hypothesis in prospective scenarios – Residential floor area by country (and for a European scenario) in 2015 and 2050.

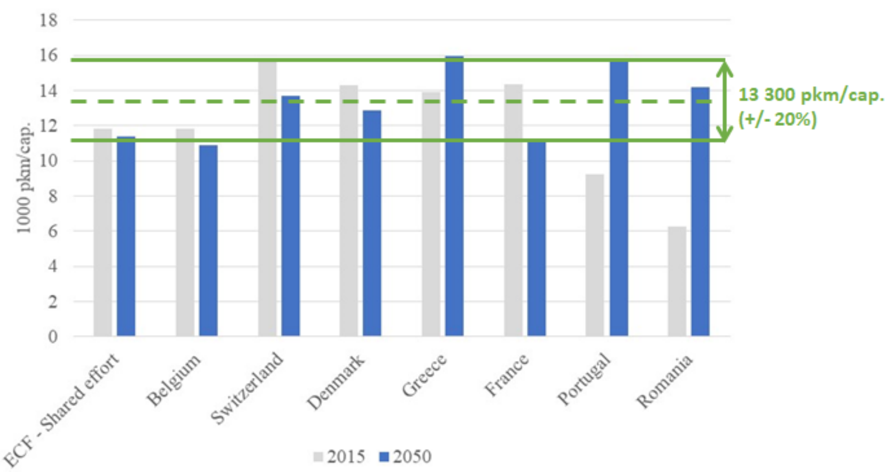


Figure 9. Illustration of the differences of sufficiency hypothesis in prospective scenarios – Passenger traffic (all modes except flying) by country (and for a European scenario) in 2015 and 2050.

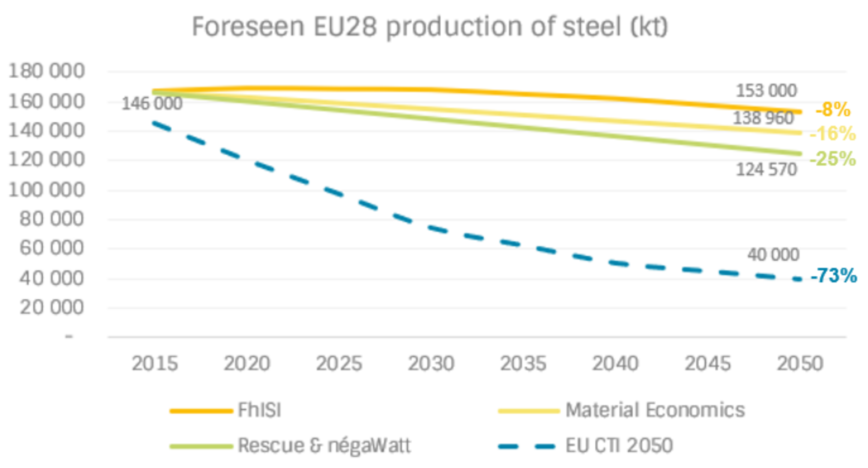


Figure 10. Building a proposed corridor of reduction of steel production on the European level.

values. As shown in the figures, a first quantification of the corridors could be obtained for these two key indicators. This is yet only a first image, that is meant to be refined through the next stages of the reinforcement and harmonisation process, with the aim of bringing as much as possible the corridors in line with a definition as "minimum consumption standards allowing every individual to live a good life, and maximum standards guaranteeing the chance to live a good life for others" (Fuchs, 2021).

In addition to corridors on targets, other indicators were used to refine the analysis and inform the level of change. A yearly evolution (CAGR or a percentage of the value in 2015) enables analysis of the stage at which the efforts are made. The percentage of reduction in comparison to a reference year (e.g. 2015) enables comparison of countries with similar initial conditions to characterise the level of effort.

Convergence in the industry sector

During the organisation of workshops on sufficiency in the industrial sector, it appeared that this sector had been poorly covered by most of national scenarios analysed throughout the partners network, with a big data gap, apart from France and Germany[6]. Further work on this sector has therefore proceeded with a top down approach, by constructing prospective stories for key basic industrial materials on the basis of major European, French and German reports on the matter (EU-CTI 2050, 2018; Umwelt Bundesamt, 2019; négaWatt, 2018a; Fraunhofer ISI, 2019).

Key energy intensive branches were prioritised according to their energy consumption and greenhouse gas emissions. Because of the lack of data and as a means for simplification, it was also assumed that the spatial distribution of industrial production infrastructure and the relationship between production and consumption will not evolve by 2050. Therefore, the reduction of industrial production due to sufficiency is assumed to be uniform across EU countries and dependent on the average level of sufficiency at the European level. The possible effect of a combination of sufficiency-related drivers with efficiency ones (energy consumption, energy intensity, circular economy, etc.), also taking into account possible relocation policies, helps developing illustrative corridors for different branches, as shown for the steel industry in Figure 10.

National partners will be able to rely on these corridors to define the right level of the parameter (percentage of reduction of the production of the considered branch, for the sufficiency leverage) taking into account the national context, to build a trajectory for industrial energy consumption. The same bottom-up approach as for other sectors will be used to integrate these trajectories in the model. This methodology therefore combines advantages of a top-down approach – mutualising the research of bibliography, and harmonising assumptions on a sector adapted to this kind of approach – and of a bottom-up approach – taking into consideration national specificities through national partners expertise.

Quantification of sufficiency

Sufficiency helps to reduce the environmental impacts of activities by reducing – to name but a few – greenhouse gas emissions, the consumption of energy and raw materials (négaWatt, 2018a), the construction of new infrastructure and housing, and thus the artificialisation of land. Although all these different outputs are not necessarily reflected in the modelling, a first step is to characterise the role of sufficiency in achieving ambitious energy reduction targets.

Measuring a specific impact of sufficiency in the consumption reductions achieved in energy transition models, and therefore its role in meeting key objectives is not straightforward: it can sometimes be complex to relate it to specific parameters of the model and to separate the impact of sufficiency from the one of efficiency, which are in practice distinct but combined. The modelling and scenario building approach that has been developed for the European scenario project was designed to help identifying sufficiency-related parameters available in the model and distinguishing between the effects of sufficiency and efficiency in the results.

First, following a categorisation that was developed by négaWatt (2018a), indicators used to describe the evolution of energy demand are considered to be sufficiency-related drivers when they touch upon one of these three categories of change:

6. In particular, in most cases, when data exist they are mostly expressed in monetary terms instead of physical volumes.

- **dimensional**, which encompasses the size and the nominal capacity of vehicles, equipment and buildings;
- **servicial**, which relates to the level of use, mainly characterized by the intensity and duration of use of buildings, equipment and goods;
- **organisational**, which encompasses for example mutualisation of equipment or building spaces, as well as the development of collective transport and walking/cycling infrastructure.

Once sufficiency and efficiency-related parameters are distinguished, their respective role can be assessed, although that implies to assume for simplicity that the effects of the various drivers are relatively independent of each other (e.g. an increase of technical efficiency of motorised vehicles is independent from the decrease of number and use of vehicles due to the availability of better cycling infrastructures which enable sufficiency behaviour).

Once the indicators are categorised as being related to either sufficiency or efficiency, the model can be run with different sets of assumptions regarding efficiency and sufficiency drivers to compare four situations: activating none, then efficiency drivers only, sufficiency drivers only, and finally both efficiency and sufficiency drivers. However, this raises the question of what implies a non-activation of drivers. A question remains for the model runs where not all drivers are activated: do the drivers selected for the model run retain over time the same values as in the reference year of the scenario (2015 in the scenario)? Or are the values set up as they would be in a business-as-usual scenario? The first option has been chosen, since no business-as-usual scenario is planned to be built in this project (considering that it is both difficult to characterise such a trajectory, as important inflexions are already under way, and difficult to project a continuation of past trends over the long term without coming to some breaking point). This option also better reflects the respective potential of sufficiency and efficiency than the comparison with a business-as-usual trajectory, as such a scenario usually includes non-negligible efficiency effects and little sufficiency.

While the model can be used to calculate separately the effects of sufficiency and efficiency, they cumulate in many cases through the multiplication of a sufficiency ratio and an efficiency ratio. Therefore, depending on the order in which we apply efficiency and sufficiency we can underestimate or overestimate one of them. To remove this obstacle, a refined calculation was elaborated, as detailed in Table 3. Such calculation is key to shed light on the respective and combined potentials of efficiency and sufficiency, particularly the latter, to contribute to sustainability objectives such as those considered in the framework of the European scenario project regarding carbon neutrality and renewable energy supply. This will eventually allow to better assess and discuss the kind of ambitious energy consumption target that is needed to meeting those goals.

Conclusion

Energy sufficiency, as a specific reflection and action on the design and level of energy services to be delivered to end-users, has a distinct and important role to play in reducing energy consumption and the related greenhouse gas emissions, as well as materials or land use. The interest for bridging the sufficiency gap, and developing a shared vision of the role it can play in meeting carbon neutrality and sustainable development goals on the European level, brought together a network of 23 partners to date, from 20 countries, to build a European-wide scenario. Bearing a common ambition for digging into the concrete potential for sufficiency and taking into account the specificity of very diverse national contexts, they progressively elaborated a set of methodological principles and some dedicated tools to support this objective.

The process started with discussions on how sufficiency can be integrated into an overall strategy to transform the energy system to a sustainable state, laying the basis of a systemic sustainability order approach. This analysis, based on a set of criteria regarding the intrinsic contribution to sustainable development goals, the way in which one transformation option potentiates or limits others, the scalability of each option through its readiness, affordability or granularity, and the building of robustness and resilience, confirmed the interest of a "sufficiency first" approach, as long as this is integrated into a consistent combination of relevant options.

Simple and robust modelling tools were then developed to allow for the building of an integrated European trajectory where the implementation of sufficiency could be explicitly described, through a bottom-up process based on existing or ad hoc national scenarios, taking into account the diversity of these exercises in terms of methodology, scope and detail. The need for a common descriptive language of these trajectories, allowing for aggregating as well as comparing them, was addressed through the development of a dedicated dashboard where, in turn, numerous sufficiency-related indicators were introduced to provide an explicit description and analysis of this dimension of the trajectories.

Table 3. Calculation of the respective role of sufficiency and efficiency in the reduction of energy consumption.

1. Level of reduction	2. Percentage of reduction	3. Respective roles
C_{ref}: Energy consumption for the reference year (2015)	Sufficiency 1st = (C_{ES}–C_{ref}) / C_{ref}	Sufficiency: average between Sufficiency 1st and Sufficiency 2nd
C_{ES}: Energy consumption with only sufficiency drivers activated	Sufficiency 2nd = (C_{final} – C_{EE}) / C_{ref}	
C_{EE}: Energy consumption with only efficiency drivers activated	Efficiency 1st = (C_{EE}–Cref) / C_{ref}	Efficiency: average between Efficiency 1st and Efficiency 2nd
C_{final}: Energy consumption with both types of drivers activated	Efficiency 2nd = (C_{final}– C_{ES}) / C_{ref}	

Through this descriptive framework and a technical dialogue about the reinforcement and harmonisation of the trajectories, the comparison of sufficiency-related indicators was used to set for the convergence of assumptions across the countries regarding energy services, to form "sufficiency corridors". A first quantification established for example reference levels around 45 m^2 floor area per person in living spaces, and 13,000 km per person per year of passenger mobility, which will further be discussed with a view both for reducing these levels if possible and getting each trajectory closer to them. The explicit and distinct identification of efficiency and sufficiency-related leverages also allows for a calculation of their respective and combined role in shifting towards long term sustainable objectives for the energy system, highlighting the possible role of dedicated energy consumption-related goals.

These methodological and operational steps pave the way for further work regarding the harmonisation and reinforcement of trajectories, their aggregation and further integration into a European vision. This will in particular lead to a more concrete discussion on the final setting of sufficiency corridors, taking into account the important differences between the current level of key sufficiency-related indicators across European countries, and the policy leverages likely to bring such a convergence. The project's findings take part in a broader research agenda. While complementary work on the building of sufficiency assumptions in the context of "catching-up economies" of Central and Eastern Europe is already under way within the CACTUS project, the methodological principles and tools elaborated to build the European scenario will also support some of the work planned in the forthcoming H2020 project FULFILL (Fundamental Decarbonisation Through Sufficiency By Lifestyle Changes), where more in-depth analysis of some social, societal and economic aspects on the micro, meso and macro-levels is planned.

References

Brown H.S. & Vergragt P.J. (2016). From consumerism to wellbeing: Toward a cultural transition? *Journal of Cleaner Production*, 132, 308–317.

Bundesministerium für Wirtschaft und Technologie (2010). *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung.*

Burke M.J. (2020). Energy-Sufficiency for a Just Transition: A Systematic Review. *Energies* 13, Nr. 10 (13): 2444.

Grandjean A., Blanchet E., Finidori E. (2014). *Étude des 4 trajectoires du DNTE – Une vision pédagogique des 4 trajectoires étudiées dans le cadre du Débat national sur la transition énergétique.* Étude pour le Ministère de l'écologie, du développement durable et de l'énergie.

Climact (2019). Introduction to the EUCalc model – Cross-Sectoral Model description and documentation. EU-Calc project.

Creutzig F., Roy J., Lamb W. F., Azevedo I. M., De Bruin W. B., Dalkmann H., … & Weber E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, 8 (4), 260–263.

Creutzig F., Callaghan M., Ramakrishnan A., Javaid A., Niamir L., Minx J., … & Wilson C. (2021). Reviewing the scope and thematic focus of 100 000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation. *Environmental Research Letters*, 16 (3), 033001.

Darby S. & Fawcett T. (2018). Energy sufficiency: an introduction – Concept paper. European council for an energy efficient economy.

Douglas M.J., Watkins S.J., Gorman D.R. & Higgins M. (2011). Are cars the new tobacco? *Journal of Public Health*, 33 (2), 160–169.

Dufournet C., Marignac Y., Toulouse E. & Förster H. (2019), Energy sufficiency: how to win the argument on potentials?, eceee Summer study proceedings, 123–131.

Duscha V., Denishchenkova A. & Wachsmuth J. (2018), Achievability of the Paris Agreement targets in the EU: demand-side reduction potentials in a carbon budget perspective, *Climate Policy* 35 (3), 1–14.

Enough (2018), Enough network overview – paper, International network for sufficiency research and policy.

Erba S., Causone F. & Armani R. (2017). The effect of weather datasets on building energy simulation outputs. *Energy Procedia*, 134, 545–554.

Erba S., Sangalli A. & Pagliano L. (2019). Present and future potential of natural night ventilation in nZEBs. IOP Conference Series: Earth and Environmental Science, 296.

EU CTI 2050. Cornet M. and Pestiaux J. – Climact, European Climate Foundation, ClimateWorks Foundation. (2018). 2050 scenario analysis using the EU CTI 2050 Roadmap Tool. Industry – Support Material for Beta-testers. Shared Effort scenario selected.

EUCalc Project. (2020). Raw materials module and manufacturing and secondary raw-materials module for EUCalc. D3.1.

European Commission (2011). *Energy roadmap 2050*, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, COM/2011/885 final.

European Commission (2018). *A Clean Planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank, COM/2018/773 final.

European Commission (2019). *The European Green Deal*, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, COM/2019/640 final.

European Commission (2021). *The European Pillar of Social Rights Action Plan.*

Eurostat (2021). Passengers Mobility Statistics – Mobility data for 12 Member States with different characteristics.

Fuchs D., Sahakian M., Gumbert T., Di Giulio A., Maniates M., Lorek S. & Graf A. (2021). *Consumption Corridors – Living a Good Life within Sustainable Limits*. Routledge Focus

Fraunhofer ISI, ICF (2019). Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation.

Grubler A., Wilson C., Bento N. et al. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy* (3), 515–527.

IEA (2020), *World Energy Outlook 2020*, International Energy Agency, Paris.

IPCC (2018), Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland.

Ivanova D., Barrett J., Wiedenhofer D., Macura B., Callaghan M. & Creutzig F. (2020). Quantifying the potential for climate change mitigation of consumption options. Environmental Research Letters, 15 (9), 093001.

Jackson T. (2017), *Prosperity without growth – Foundations for the economy of tomorrow*. Routledge, second edition.

Jackson T. (2019), *Zero carbon sooner – The case for an early zero carbon target for the UK*, CUSP Guilford: University of Surrey.

Lade S.J., Steffen W., de Vries W. et al. Human impacts on planetary boundaries amplified by Earth system interactions. *Nat Sustain* 3, 119–128 (2020).

Marignac Y. (2019). Energy sufficiency as part of climate action. Technical note n° 8, *Climate Recon 2050 – Dialogues on Pathways and Policy.*

Max-Neef M., Elizalde A., Hopenhayn M. (1991). *Human Scale Development; conception, application and further reflections*, New York & London, The Apex Press.

négaWatt. (2018a). Scénario négaWatt 2017–2050. Hypothèses et résultats.

négaWatt (2018b). Energy sufficiency: towards a more sustainable and fair society.

négaWatt (2020). European scenario – Description of the simplified modelling tool.

Pagliano L. & Erba S. (2019). Energy sufficiency in (strongly intertwined) building and city design – examples for temperate and Mediterranean climates. eceee Summer Study Proceedings 2019, 2019–June, 1505–1514.

Raworth K. (2012). A safe and just space for humanity: can we live within the doughnut? Oxfam.

Raworth K. (2017), Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist. Random House Business.

Rockström J., Steffen W., Noone K., Persson Å. et al. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society* 14 (2): 32

Sachs W. (1993). Die vier E's: Merkposten für einen maßvollen Wirtschaftsstil. *Politische ökologi* 11 (33), 69–72.

Sachs W. (1995). From efficiency to sufficiency. *Resurgence*, 171.

Samadi S., Gröne M., Schneidewind U., Luhmann H., Venjakob J., Best B. (2016). Sufficiency in energy scenario studies: Taking the potential benefits of lifestyle changes into account. *Technological Forecasting & Social Change*.

Samadi S., Terrapon-Pfaff J., Lechtenböhmer S., Knoop K. (2018). Long-term low greenhouse gas emission development strategies for achieving the 1.5 °C target – insights from a comparison of German bottom-up energy scenarios. *Carbon Management*.

Sfakianaki A., Santamouris M., Hutchins M., Nichol F., Wilson M., Pagliano L., Pohl W., Alexandre J. L. & Freire A. (2011). Energy Consumption Variation due to Different Thermal Comfort Categorization Introduced by European Standard EN 15251 for New Building Design and Major Rehabilitations. *International Journal of Ventilation*, 10 (2), 195–204.

Sovacool B.K., Martiskainen M., Hook A.& Baker L. (2020). Beyond cost and carbon: The multidimensional co-benefits of low carbon transitions in Europe, *Ecological Economics*, Vol. 169, 106529.

Spengler L. (2016), Two types of 'enough': sufficiency as minimum and maximum, Environmental Politics, 25:5, 921–940.

Salvia G., Morello E., Rotondo F., … Erba S., Pagliano L. (2020), Performance gap and occupant behavior in building retrofit: Focus on dynamics of change and continuity in the practice of indoor heating, *Sustainability* (Switzerland), 2020, 12(14), 5820.

Thema, J., Suerkemper, F., Couder, J., Mzavanadze, N., Chatterjee, S., Teubler, J., Thomas, S., Ürge-Vorsatz, D., Hansen M.B., Bouzarovski S., Rasch J.; Wilke S. The Multiple Benefits of the 2030 EU Energy Efficiency Potential. *Energies* 2019, *12*, 2798.

Thomas S., Thema J., Brischke LA. et al. (2019). Energy sufficiency policy for residential electricity use and per-capita dwelling size. *Energy Efficiency* 12, 1123–1149.

Toulouse E., Sahakian M., Bohnenberger K., Bierwirth A., Lorek S., Leuser L. (2019). Energy sufficiency: how can research better help and inform policy-making?. *eceee Summer Study proceedings*.

Umweltbundesamt. (2019). Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE. GreenSupreme scenario selected.

Williams J. & Waisman H. (2017). *2050 Pathways: A Handbook*. 2050 Pathway Platform.

Wilson C., Grubler A., Bento N., Healey S., De Stercke S. & Zimm C. (2020). Granular technologies to accelerate decarbonization. *Science* 03 Apr 2020: Vol. 368, Issue 6486, pp. 36–39

Zell-Ziegler C., Förster H. (2018). Mit Suffizienz mehr Klimaschutz modellieren. German Umweltbundesamtes.

Zell-Ziegler C., Thema J., Best B., Wiese F., Lage J., Schmidt A., Toulouse E., Stagl S. (submitted to Energy Policy): Enough? The role of sufficiency in energy and climate plans of European countries.