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Towards optimal 1.5°and 2°C emission pathways for individual countries: a Finland case study

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Highlights

- We downscale regional IAMs results to the country level with a new model: SIAMESE
- Results over the historical period confirm the validity of our approach
- Using Finland as an example, we analyse CO_2 emissions for both 1.5°C and 2°C pathways.
- We calculate the remaining carbon budget until mid-century and 2100 for the example case of Finland.

Abstract

Nationally Determined Contributions (NDCs) submitted so far under the Paris Agreement are not in line with its long-term temperature goal. To bridge this gap, countries are required to provide regular updates and enhancements of their long-term targets and strategies, based on scientific assessments.

The goal of this paper is to demonstrate a policy-support approach for evaluating NDCs and guiding enhanced ambition. The approach rests on deriving national targets in line with the Paris Agreement by downscaling regional results of Integrated Assessment Models (IAMs) to the country level. The method of downscaling relies on a reduced complexity IAM: SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator).

We apply the approach to an EU28 member state – Finland – with the aim of providing useful insights for policy makers to consider cost-effective mitigation options. Results over the historical period confirm that our approach is valid when national policies are similar to those across the larger IAM region, but must include country-specific circumstances. Strengths and limitations of the approach are discussed.

We assess the remaining carbon budget and analyse the different implications of 2°C and 1.5°C global warming limits for the emissions pathway and energy mix in Finland over the 21st century.

Keywords: Paris Agreement, Integrated Assessment Models, downscaling, energy sector, 1.5°C pathway, mitigation.

1 - Introduction

IAMs (Integrated Assessment Models) play a crucial role in policy relevant assessment of mitigation technologies, policies and different modes of international cooperation to achieve climate and sustainable development goals (van Vuuren 2015, von Stechow et al. 2016). IAMs have the key benefit for policy makers of showing the interactions between all key systems and sectors at the scale of large nations, regions and globally. Applying the insights from these models to sub-regional and small national scales has remained difficult due to several factors: the computational intensity of higher resolution, the complexity of adjusting models to higher resolution and the regional structure of IAMs which often does not relate well to politically and policy relevant regions. Although IAMs themselves are a highly abstract representation of the energy and economic systems and how these couple to climate change mitigation policies, we accept as a starting point the premises of IAMs and concentrate here on an approach for improving the relevance of IAMs at the more fine-grained geographical scale of individual countries.

As momentum builds toward implementing the Paris Agreement, the urgency of applying policy relevant insights of IAMs towards enhanced/intensified action and ambition at the national scale increases. The PA specifies its long-term temperature goal (LTTG) as holding global mean temperature increase well below 2^{o}C and pursuing efforts to limit it to 1.5^{o}C (Article 2.1). This will require national actions, formulated in Nationally Determined Contributions (NDCs), to jointly lead to global emissions that peak by 2020, reduce rapidly thereafter, and approach zero CO_2 emissions globally by around mid-century and zero total GHG emissions about a decade later (Rogelj et al 2015b; Rogelj et al 2018, Rogelj et al 2018b). National governments will need to determine how their plans under the Paris Agreement match the global goals of that agreement, and how connected changes in their energy system relate in timing and scale of deployment related to the larger global transformations.

Here, we outline a novel approach bridging between the regional scale of an IAM to that of a small country within a region. At the same time, we provide a tool to assist policy makers and stakeholders in understanding options for energy system transformation to reduce CO_2 emissions consistent with the Paris Agreement: SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator), a new model able to downscale the primary energy consumption and emissions from IAM scenarios to the country level. Aggregated primary energy consumption includes energy used for power generation, final energy consumption and other energy sectors[1]. Enhancing the resolution of IAMs to sub-regional levels would have two key benefits.

First, if available at the country level, IAM results for Paris Agreement compatible pathways could be used as inputs to national-level, and in some cases sub national-level (regional), policy making. This would assist policy makers in assessing the consistency and timing of policy and technology options in relation to global and regional options, ensuring complete consistency with science-based pathways of other countries and regions, within global constraints that ensure compatibility with the Paris Agreement LTTG. Such knowledge could help avoid costly lock-in effects, as some measures may appear attractive based on national-level analyses of emission targets, even though they might be not compatible with the global long-term target of the Paris Agreement.

Secondly, the Paris Agreement provides a five-yearly global stock-take, where the aggregate level of action of countries is evaluated, with outputs from the stock-take meant to inform countries when updating and increasing the level of ambition of their NDCs. With the facilitative (Talanoa) dialogue having started in 2018, countries should regularly deliver science-based assessment of parties'

[1] Excluding international aviation and marine bunkers.

contributions and their relation with the long term temperature target and mitigation goals of the Paris Agreement (Schleussner et al. 2016). Insights from IAMs could be very important for evaluating how individual countries are tracking in terms of their decarbonisation and their long-term climate policies, against national level cost-optimal domestic emission and energy system pathways. This would also provide the technical capability for the comparison of NDCs to cost-effective national pathways under a global temperature guardrail.

Currently there is an urgent need to enhance ambition in line with best available science, as the collective mitigation efforts from (I)NDCs ((Intended) Nationally Determined Contribution) are, in aggregate, not in line with 2°C, let alone 1.5°C. Globally aggregated NDC pledges could lead to a global median warming of 3°C by 2100 (Rogelj et al. 2016, UNFCCC 2016, Climate Action Tracker 2018), with 2030 emissions levels ranging from 52 to 58 GtCO2e/yr globally (Rogelj et al 2017, Climate Action Tracker 2018, Olhoff et al 2018, Rogelj et al 2018b) compared to the 25-30 GtCO2e/yr (interquartile) range from the IPCC SR 1.5°C SPM (Allen et al 2018).

SIAMESE helps satisfying these needs by providing a computationally efficient, high-level approach consistent with the driving equations of IAMs. In this paper, we provide a 'proof of concept', evaluating the SIAMESE results over the historical period 1970-2015 and applying to both a 2^{o}C (66% probability to stay below 2°C) and a Paris Agreement 1.5°C compatible pathway (50% probability to be below 1.5°C in 2100) for Finland until 2100.

2 Literature review

Downscaling methods have been employed with physical models of climate change impacts based on Global Climate Models (GCMs) (Ekstrom et al 2015), as well as for the analysis of emissions pathways (van Vuuren 2007, Grübler et al 2007, Fujimori et al 2017). We can broadly classify approaches in terms of simple downscaling algorithms (Gaffin et al 2004, Höhne and Ullrich 2005), methods of intermediate complexity such as statistical models (Wilby et al 2004) or on conditional modelling (Bollen 2004, Carter 2004). The latter can be further classified either in "full models" at lower level of disaggregation or in "fully coupled models" at national or grid scales (van Vuuren et al 2010). A "rule of thumb" is that with limited amounts of data available, a simple algorithm should be preferred (van Vuuren et al 2007).

Downscaling approaches should satisfy three main criteria, including consistency with local-scale data (e.g. with the historical period), consistency with the "mother" scenario (original source of data) and internal consistency and transparency (in terms of a well-defined methodology) (van Vuuren et al 2010). Additional criteria include the need for plausibility (in terms of avoiding violation of physical boundary conditions), ability to be scenario-specific, and the capability to describe structural changes (Grübler et al 2007).

The literature in the past relied mostly on simple algorithms, although they have been criticised (van Vuuren et al 2007) as leading to unsatisfactory results or unrealistic growth rates. Authors tackled this issue by using a combination of these algorithms or scenario-based algorithms (van Vuuren et al 2007, Fujimori 2017), leading to more credible results. However, a main criticism remains as those algorithms are usually based on fixed simple rules and are not able to describe themselves the physical or economic dynamics behind those pathways (van Vuuren et al 2007, van Vuuren et al 2010).

As increasing amount of data are now becoming publicly available – relevant for the present work are the IPCC SR 1.5C database (Huppmann et al 2018, Huppmann et al 2018b, Rogelj et al 2018b) in conjunction with the database of Shared Socio-economic Pathways (SSPs) storylines (O'Neill et al

2014, Fricko et al 2016, Bauer et al 2016, Bauer et al 2017, Riahi et al 2017, Dellink et al 2017). Using these scenario data, this paper relies on a "conditional modelling" downscaling approach with boundary conditions from IAMs. To this end we employ a reduced complexity model – SIAMESE – operating at finer geographical scales and that is conditional on results (and assumptions) from IAMs. SIAMESE mimics the general framework and philosophy of IAMs while using a coherent set of assumptions based on SSP storylines. At the same time, SIAMESE makes sure that sum of countries grouping comply with the original IAM regions. To our knowledge conditional modelling have been used so far only for downscaling climate change impacts analysis (Carter 2004), or GDP and socioeconomic data (Bollen 2004, Gaffin et al 2004, Grübler et al 2007, Sanstad et al 2009) or land use emissions pathways (EPA 2009, Hasegawa et al 2017). This paper is a therefore a first attempt to use a conditional modelling approach for mitigation scenarios and analysis of carbon emissions pathways and the associated primary energy mix. Our approach also allows for including country-specific circumstances – such as current policies in place and other physical boundaries – which represents a key step forward compared to simple algorithm approaches.

The next section presents the SIAMESE model, employed in this paper for conditional downscaling of IAM scenarios. A main critique with respect to conditional downscaling approaches relates to increasing complexity and increasing number of associated parameters and assumptions (van Vuuren et al 2007, van Vuuren et al 2010). In this context, we show that SIAMESE can be described with only six main equations (see Appendix A) and therefore allows for a manageable level of complexity. Since SIAMESE is essentially a reduced complexity IAM, most (if not all) of its parameters can be harmonised in line with the IAM used for the driving condition scenario, or with SSP storylines.

3 - Methods

IAMs determine an optimal energy mix and GHG emission pathways consistent with a temperature limit, carbon budget, or other goal, while minimising global mitigation costs (welfare maximisation approach). Among the models in the IAM framework, some divide the world into large aggregate regions (e.g. MESSAGE, ReMIND, WITCH) and others provide country-level results, but only for the major emitters (e.g. DNE21+, GCAM, GEM-E3, IMAGE) (Van Soest et. al. 2016, Van Soest et al. 2017).

In this paper, we rely on a model-based (conditional modelling) approach to downscale IAM results to the country level. Our methodology can be in principle applied to any energy-system economic model and it is based on a reduced complexity IAM: SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator). Like most IAMs, SIAMESE is a Ramsey-type optimisation model with perfect foresight. SIAMESE determines the optimal energy consumption (and carbon emissions) at the country level by maximising welfare in all countries belonging to the same IAM region. The SIAMESE production function resembles those of other IAMs, although it is more simplified. This reduced-complexity framework allows SIAMESE to run with a more detailed (flexible) regional resolution and it can be virtually applied to any country (or sub-nation regions).

While downscaling the results to the country level, SIAMESE considers future GDP and population developments at the country level, based on SSP storylines developed by the IAM community (Fricko et al 2016), as well as observed energy consumption at the base year (by fuel).

Inputs to SIAMESE include:

- Regional IAMs boundaries condition: Projected energy consumption over time for the IAM region (e.g., WEU), for each fuel.

- Country-specific energy consumption data at the base year.
- Country-specific GDP and population projections over time (e.g., Finland, Rest).

Key outputs from SIAMESE include:

- Projected energy consumption for all countries (e.g. Finland and Rest), by fuel.
- CO_2 emissions excl. LULUCF (based on emissions factors and energy consumption by fuel).

In general, SIAMESE tends to allocate more energy in countries with higher GDP and population growth (appendix A, equation A.1), which ultimately leads to higher emissions. For example, if we were to downscale a hypothetical region made up by two identical countries (with the same energy mix at the base year and the same GDP and population projections over time), SIAMESE would allocate energy consumption (and CO_2 emissions) equally. Results would start to differ over time only if we allow for different GDP and/or population growths across countries (or if we add specific constraints at the country level).

SIAMESE is calibrated to reflect the observed energy consumption at the base year (see Appendix A, "static calibration"). In a sense, this calibration process sets up "preferences" regarding the energy mix at the country level (reflecting present-day infrastructures and resources availability), and introduces some inertia in the transition towards a low carbon pathway.

In a similar manner we also "harmonise" SIAMESE so that the optimal solution over time (at the regional level) coincides with the boundary conditions from IAMs. To do so, we determine the energy prices associated with the "optimal" energy consumption results from IAMs at the regional level. More precisely, under a welfare maximisation approach the "optimal" energy consumption for a given fuel (in a given point in time) decreases monotonically (all else being equal), as the energy price increases (and vice versa). In this context, SIAMESE equalises the energy prices (marginal cost) across countries (for each fuel and time), so that the optimal solution at the regional level from SIAMESE coincides with the IAM results.

By equalising the marginal costs of energy across countries, SIAMESE harmonises countries' efforts (and policies) in the transition towards a low-carbon pathway. For instance, this assumption tends to maintain the same "phase out dates" for each fossil fuel technologies across countries, in line with the regional IAMs results. In a similar manner, it also preserves the same "phase in" dates, for new technologies which are currently not available at scale (e.g. biomass with CCS).

We conclude that in its standard version SIAMESE assumes "harmonised" policies in place in all countries belonging to the same IAM region. In this paper we assess the validity of this assumption in Finland, by comparing SIAMESE simulations outcomes against observed energy data over the historical period 1970-2015 (section 4).

In the real world though, mitigation efforts differ across countries, because of the bottom-up nature of the UNFCCC negotiation process which allows for nationally-determined emissions targets (e.g. NDCs) and specific policies in place at the country level. To better reflect real world developments, we can enhance the standard version of SIAMESE by including specific policies in place (as well as other physical constraints), as we did for the simulations over the 21st century (section 5). One would expect, on the other hand, that as countries step up implementation of the Paris Agreement moving toward the LTTG of 1.5°C, overall policies will also converge between countries because of the clear decarbonisation pathway needed for that target. For example, under Paris Agreement compatible pathways (with no or low overshoot), global GHG emissions should decline by 38-55% by 2030 below 2010 levels (Allen et al 2018).

In this paper we downscale the IAM MESSAGE 1.5C and 2C emissions pathways (Rogelj et al. 2013, Rogelj et al. 2015) by using SIAMESE. MESSAGE provides results for eleven key macro regions. In the MESSAGE model, Finland belongs to the "WEU" (Western Europe) region, which is comprised of 32 countries in total (including most, but not all, of the European Union 28 member states). Finland represents a relatively small economy compared to the broader WEU region[2], which makes it an interesting case study to test our model. SIAMESE assumes a starting point that the WEU region of the MESSAGE model can be decomposed into two inner regions: Finland and Rest of Western Europe. Then we derive the primary energy consumption (and the fuel mix) of Finland based on 1) the MESSAGE model results of the WEU region and 2) Socio-economic (GDP and population) projections for both Finland and the rest of the WEU region. Finally, SIAMESE is calibrated to replicate the observed energy consumption in Finland at the base year. For future scenarios, the base year of SIAMESE is 2010 with a 10 years' time step (section 5). However, SIAMESE can be calibrated according to different base years and can also be run with different time steps (e.g., one year), as we do for simulations over the historical period (Section 4).

In terms of the equations, SIAMESE mimics the structure of IAMs, in which a representative agent maximises welfare over time under a perfect foresight assumption. For additional details on SIAMESE and the list of equations please refer to Appendix A. Details of the model set-up and calibration parameters are shown in Appendix B.

4 – Results over historical period

In this section, we evaluate if the assumption of "uniform policies" between Finland and the Western European region holds true over the period 1970-2015, by comparing the output of SIAMESE with the observed energy consumption data.

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[2] Finland accounts for roughly 1% of both GDP and population of the WEU region.

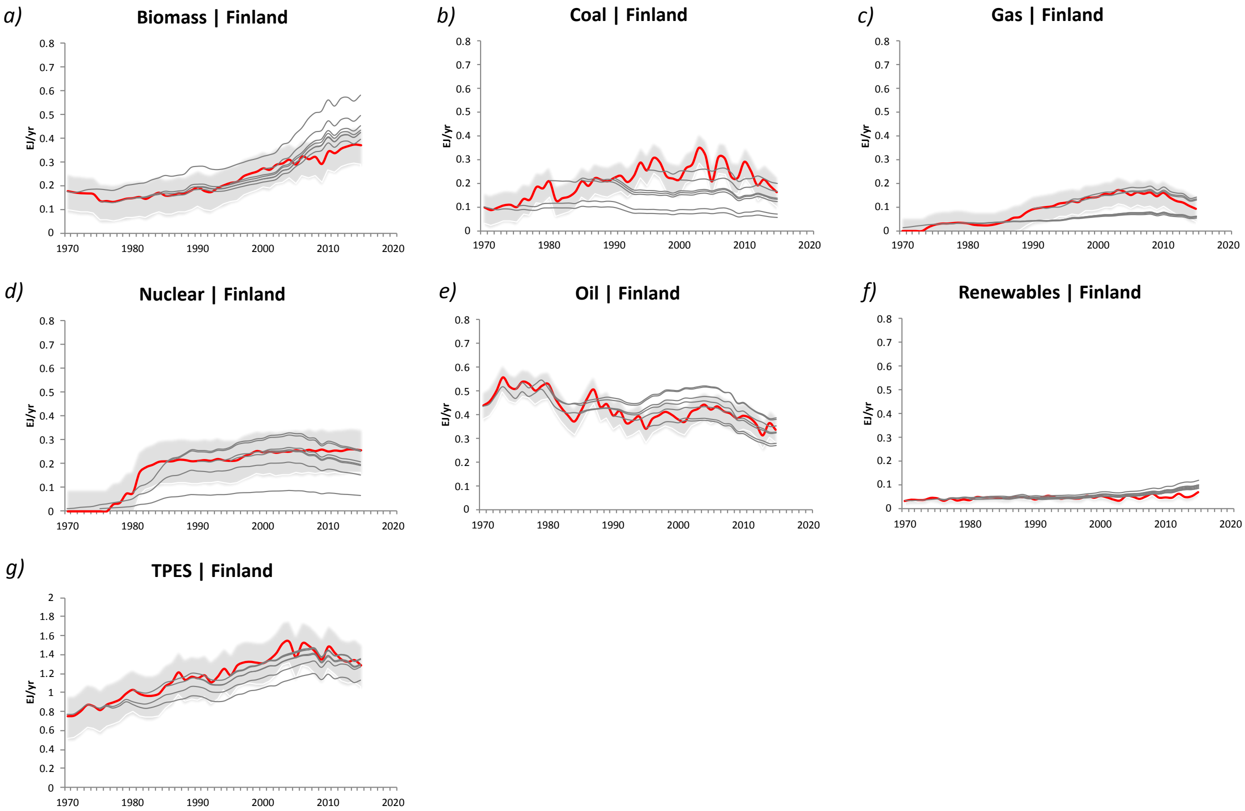

Figure 1 - SIAMESE model vs observed data. A red line depicts the historical data for each fuel: biomass (a), coal (b), gas (c), nuclear (d), oil (e) and renewables (f) as well as the Total Primary Energy Supply (g), source: IEA 2016. The light grey range represents the historical volatility of data (+/- one standard deviation). Grey lines represent simulations from SIAMESE starting from different base years: 1970, 1975,1980, 1985, 1990, 1995 and 2000.

To do so, instead of using the MESSAGE model results for the WEU region as input to SIAMESE, we rely on observed historical data for energy consumption (source: IEA) as well as for GDP and population (source: WDI 2016). Since historical data are available at a yearly basis, we run SIAMESE using a time step of one year[3]. Based on the historical data, we compute the aggregate energy consumption, as well as GDP and population data for the WEU region. Then, we downscale the results from WEU to Finland by using SIAMESE.

Figure 1 shows the simulated energy consumption from SIAMESE (grey lines) starting from different base years along with the observed historical data (red line, source IEA 2016).

[3] Conversely, for future scenarios (section 5) SIAMESE employs a time step of 10 years (in line with the temporal resolution of IAMs).

We find a good level of agreement between SIAMESE model results and the observed historical energy consumption data in Finland during the period 1970-2015, but for some energy carriers, SIAMESE output deviates from actual data substantially, depending on the base year.

On the one hand, SIAMESE can emulate the key trends of Total Primary Energy Supply (TPES) in Finland, as well as individual fuels like oil and biomass. It also provides reasonable results for gas and nuclear, despite these coming on line in the primary energy mix only in the late 1970s. In principle, low initial shares pose challenges for the static calibration of the model[4] and explains why the SIAMESE results for these fuels are much closer to actual data for base years later than the late 1970s.

All in all, SIAMESE is able to better replicate historical data when Finland's policies and behaviour mirror that of the "average" WEU (Western European) region. Indeed, larger deviations between the SIAMESE performance and observed historical data might hint at domestic policies that are not aligned with the "average" IAM region. For example, SIAMESE tends to overestimate consumption of renewables in Finland in the last decade. In a sense, SIAMESE suggests that Finland is lagging behind in the deployment of renewables compared to other Western European countries[5] (that provide the driving conditions for downscaling to Finland), a trend that is confirmed by recent literature (Haukkala 2015). In other words, SIAMESE is trying to "make" Finland behave more like the rest of the WEU in this respect. This is very relevant when considering the projections in the next section: The results above confirm the principle that our approach for downscaling is valid when national policies are (assumed to be) similar to those across the larger region, but must take into account additional constraints to reflect national circumstance and national long-term policy

[4] When energy consumption is equal to zero, we assume a value of 0.01 EJ/yr.

[5] SIAMESE allocates energy consumption while equalising the marginal cost across all the countries belonging to the same region (in this case WEU). A lower consumption compared to what SIAMESE identified as "optimal" entail a lower cost burden (e.g. for renewable subsidies) compared to other European countries.

objectives over the next decades. This characteristic should not be seen as a weakness of SIAMESE, but rather an unavoidable feature of looking more closely into the results of coarsely-resolved IAMs.

In that context, one has to keep in mind that SIAMESE is designed to provide long-term scenarios. Therefore, just like IAMs, it is not expected or able to capture the high short-term volatility of some historical data series (e.g. coal consumption), which could have been affected by temporary domestic policies such as tax treatment. For example, peat[6] – as being one of the few domestic energy sources – had received substantial financial support in the form of tax exemptions and public subsidies (OECD 1999). Recently, Finland decided to ban coal consumption by 2030, in order to enhance air quality and comply with long-term decarbonisation strategies (Government of Finland 2016), another policy that is important in the context of climate change mitigation strategies, but not representative of the "average" policy regimes of WEU countries.

Certainly, SIAMESE is not able to "predict" future policies at the country level. While downscaling the results, SIAMESE equalises the marginal cost of energy in all countries (cost-optimal solution) belonging to the same region (e.g. WEU). In a sense, SIAMESE assumes "uniform" policies in all countries. This assumption might hold true for the member states of the EU, which share common rules (e.g. EU directives) for domestic markets (such as gas and electricity). However, the adoption of EU policies is not always uniform, with countries that might be slower in adopting EU directives. Also, while looking at Figure 1 it is important to bear in mind that Finland joined the EU only in 1995.

In this respect, the WEU region of the MESSAGE model comprises several countries belonging to the European Union (such as Finland) as well as countries that are not part of the EU (such as Turkey). For example, results of downscaling the WEU region to Turkey (instead of Finland),

[6] SIAMESE considers peat as part of total coal consumption.

indicates larger deviations between the SIAMESE results and the observed historical data, suggesting more fundamental differences in implemented policies (Appendix C), and illustrating the potential limits of downscaling.

Finally, historical simulations show that that technologies that are in an early stage of development, or not present at all in the energy mix (such as nuclear and gas in Finland in the early 70s) are more subject to uncertainty than others: in this case country-level projections are strongly affected by the initial conditions (static calibration) of the model.

These findings and insights guide our modelling assumptions and interpretations of results for the scenarios over the 21st century. For example, for new technologies like CCS, instead of calibrating CCS technologies based on observed data at the base year (currently not available at scale) we derive the share of CCS and non-ccs technologies (within fuels) in a proportional manner, based on the results of the WEU region from MESSAGE[7]. In other words, we implicitly assume that CCS technologies for a given fuel (e.g. biomass with CCS) will be mainly deployed in countries where that particular fuel (e.g. biomass) is currently used. The percentage of biomass with (or without) CCS is based on the IAM regional data. In the absence of more detailed country-specific information, this is a way of getting credible results in line with the regional average IAM data.

To conclude, while producing future scenarios, it is important to take into account specific market characteristics and policies in place at the country level, as well as particular deviations of national policies from the encompassing region, if this can be anticipated or captured in scenario variants and additional SIAMESE model constraints.

[7] In Finland we assume an upper bound on CCS sequestration of 45 MtCO2/yr based on Arasto et al (2014). Therefore, the CCS ratio does not fully coincide with the MESSAGE model results for the WEU region.

5 – Results for 21st century scenario projections

This section shows the results under a 2°C and a 1.5°C scenario in Finland. In contrast to the model runs for section 4, we now run SIAMESE using a time step of 10 years, in line with typical IAM temporal resolution. Also, we enhance SIAMESE by introducing country-specific policies in place, as well as geophysical constraints. In particular, we assume a phase-out of coal use in Finland by 2030, as well as an upper bound on carbon storage in Finland of 45 $MtCO_2$/yr (Arasto et al. 2014)[8].

Results over the 21st century show that the use of biomass energy, both with and without CCS, is a main driver of emissions reductions in Finland (Figure 4). By 2100, biomass would meet roughly 70% of Finnish energy consumption (of which half of it is coupled with CCS) in both 2°C and 1.5°C scenarios, compared to a WEU average of 25% (of which 60% is with CCS). Although the 2°C and 1.5°C pathways might look similar in the long-term, important differences arise in the short- and medium-term.

Under a 1.5°C scenario, Finnish CO_2 emissions would need to go below zero by 2040 – ten years earlier than a 2°C scenario – and stabilise at around -35 $MtCO_2$/yr in the second half of the century. SIAMESE envisions a phase out of oil in Finland by 2060, whereas nuclear remains in the energy mix at about current levels (Figures 3a and 3b). These results are in line with the MESSAGE 1.5°C scenario for the WEU region. Unabated gas remains in the primary energy mix throughout the 21st century, but at a substantially lower level than present. CCS technologies for gas come online at low level in the 2020s and then at scale until phase-out around 2080. Overall biomass consumption, which already accounts for roughly a fourth of energy consumption in Finland, is expected to increase over time but at a slower pace compared to the average WEU region. Biomass with CCS

[8] Arasto and co-authors (2014) estimated a technical potential of biomass with CCS of 45$MtCO_2$ in Finland in 2030. To be conservative, this paper considers an upper bound of 45 $MtCO_2$/yr on total of CO_2 storage – whether from fossil CCS or biomass with CCS – due to limited geological storage potential in Finland (Teir at al. 2010). Capture CO_2 could be also transported via pipeline to Norway (Kjärstad, et al. 2011) although SIAMESE does not explicitly model CO_2 transportation costs.

starts at a low level in the 2020s and scaled up most rapidly from 2030 until 2040, with slower growth thereafter (also due to the upper bound on sustainable carbon storage).

The 2°C scenario shows similar patterns to the 1.5°C pathway, but deploys BECCS (biomass with CCS) about 10 years later. Oil remains in the energy mix until 2070, ten years later than in the 1.5°C pathway, whereas in this pathway nuclear is progressively shut down in the first half of the century both in Finland and Western Europe (Figures 2a and 2b).

In Finland coal is to be phased out by 2030 under current government policies. SIAMESE estimates that in the absence of further policies, for example accelerated electrical vehicle uptake, oil would remain in the energy mix until 2060 (1.5°C) or 2070 (2°C pathway). The coal phase-out in Finland takes place ahead of the EU as a whole, because we constrained the model to reflect Finland's existing policies on this topic. On the other hand, the oil phase-out by 2060 or 2070 (1.5°C and 2°C respectively) is in line with the EU as a whole in the driving IAM scenario.

By the end of the century the energy mix will be dominated by renewables and biomass. To achieve this will require Finland to increase investments in biomass, hydropower, geothermal, wind and solar energy. The declining cost of renewable electricity in the EU, as shown by recent cost estimate (IRENA 2018), provides one promising avenue for investment in energy system transformation.

Based on those scenarios, we can compute the remaining fossil fuel carbon budget[9] in Finland (Table 1). Under a 2°C scenario the remaining carbon budget is about 0.9 $GtCO_2$ for the first half of the century, from 2018-2050. Under a 1.5°C pathway the carbon budget should not exceed 0.4$GtCO_2$ for the same period. For the second half of the century (2050-2100), the remaining Finnish carbon

[9] SIAMESE simulations over the 21st century entail a time step of 10 years. We assume a linear interpolation for the years in-between.

budget is negative in both 2°C and 1.5°C scenarios (-1.8 and -1.9 $GtCO_2$ respectively), as negative emission technologies are expected to compensate for sources of emissions.

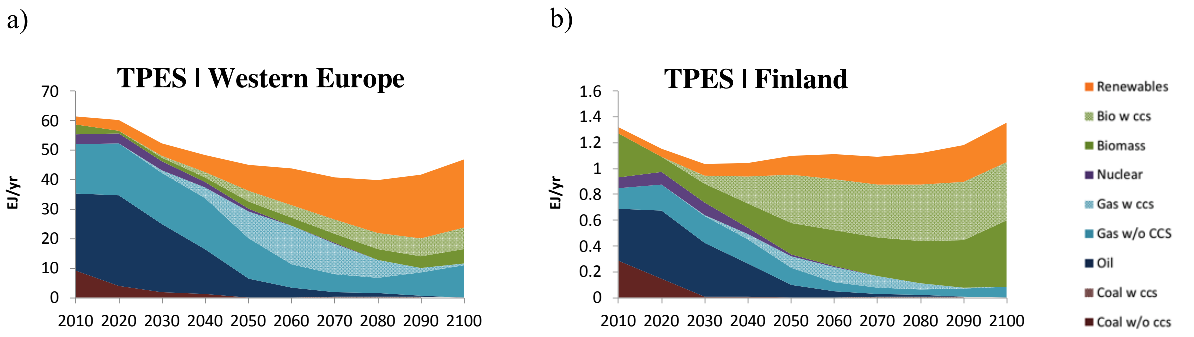

Figure 2 – Primary energy mix in WEU from MESSAGE (a) and Finland from SIAMESE (b) under a 2°C compatible pathway.

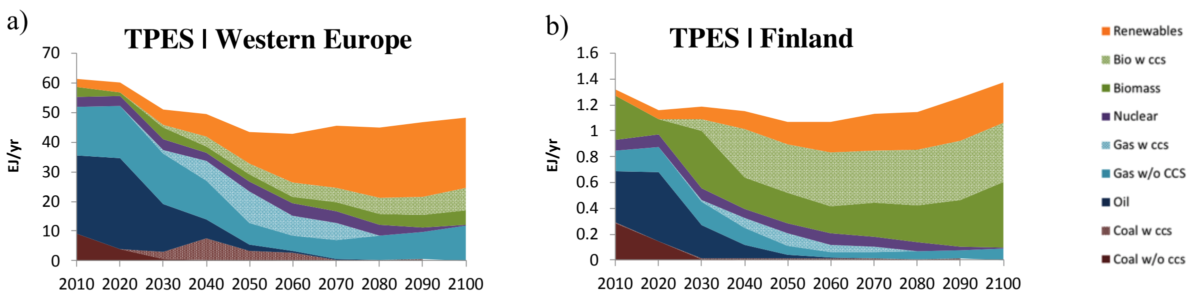

Figure 3 – Primary energy mix in WEU from MESSAGE (a) and Finland from SIAMESE (b) under a 1.5°C compatible pathway

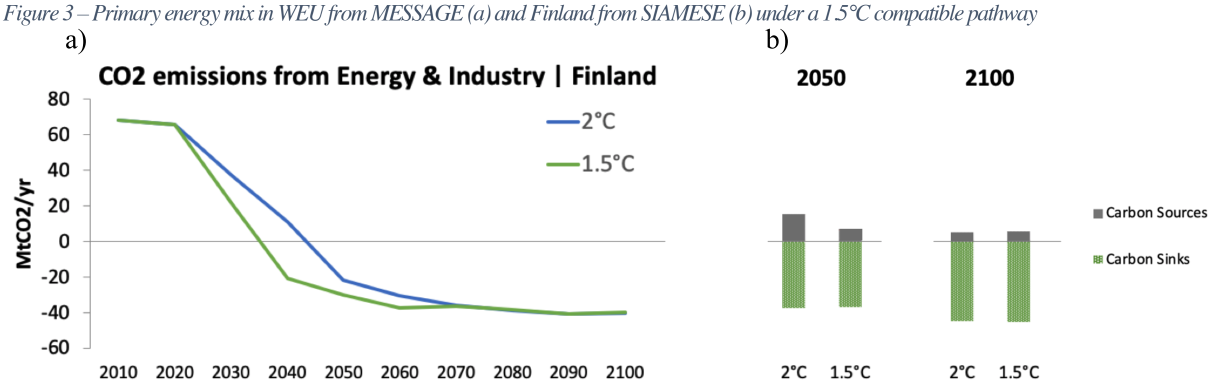

Figure 4 – Total CO_2 emissions from energy and industry in Finland across scenarios (a) and carbon emissions sources and sinks in 2050 and 2100 (b) under 2°C and 1.5°C pathways.

Scenario / period	Finland's carbon budget ($GtCO_2$)	
	2018-2050	2050-2100
2°C	0.9	-1.8

1.5°C	0.4	-1.9

Table 1 – Finland's carbon budget (excluding LULUCF - Land Use Land Use Change and Forestry) across different scenarios for the first (2018-2050) and second half of the century (own calculations based on SIAMESE).

6 – Conclusion and Policy Implications

We have presented a reduced complexity, model-based approach to downscale the results of IAMs to the country level. By using SIAMESE, we provided a 1.5°C emission pathway for Finland, based on input data for Western Europe from the IAM MESSAGE. A key strength of SIAMESE is its ability to provide country-level CO_2 emission pathways consistent with IAM results both at the global and regional levels, under a common set of policies and assumptions (e.g. SSP storylines, technological availability). SIAMESE does not require long historical data series, which makes it particularly suitable in countries with lack of historical data.

If country-specific measures are not taken into account, SIAMESE implicitly assumes "uniform" energy and climate policies in all countries belonging to the same region (e.g. WEU). This assumption was first explored to interpret the SIAMESE results in the context of historical data for the period 1970-2015. We found that SIAMESE captures relatively well the key trends in historical energy consumption in Finland. However, energy consumption can be affected by country-specific measures, such as subsidies to indigenous sources of energy (e.g. peat, in some areas of Finland) and this is apparent in the differences between historical time series and the SIAMESE results that do not take into account specific national circumstances.

For the scenarios over the 21st century we have introduced country-specific policies (as well as geophysical constraints) in order to anticipate expected energy developments. Under a 1.5°C scenario (holding warming below 2°C with about an 80% probability and with a 50% probability to be below 1.5°C in 2100), we show that CO_2 emissions from energy and industry would need to decline rapidly and drop below zero by 2040. Under a 2°C scenario (66% probability to hold warming below 2°C), the timing of zero emission would be delayed by roughly a decade, a delay confirmed for IAM regions and globally by earlier literature (Rogelj et al. 2015).

A key difference between 2°C and 1.5°C compatible pathways is the rate of decarbonisation in the first half of the century. Under a 1.5°C pathway, CO_2 emissions from fossil fuel would need to decline by roughly 70% by 2030 below 2010 levels, compared to 45% under a 2°C pathway. The remaining budget for the period 2018-2050, is around 0.4 $GtCO_2$ under a 1.5°C pathway, compared to 0.9 $GtCO_2$ under 2°C for the period 2018-2050.

Given these large differences in the carbon budget in the first half of the century and the need for short-term emissions reductions– also confirmed globally by the IPCC Special Report on 1.5°C (Allen et al 2018) – enhancing the European NDC as well as national targets is required to limit warming to 1.5°C. This would also reduce the need for negative emission technologies in the long-term. While renewable energy is already a cost-effective decarbonisation option in many cases, additional policies will be needed to foster negative emission, or other carbon dioxide removal technologies.

If biomass with CCS technologies would not be deployed in the coming years, Finland would need to find other ways to achieve a balance between sinks and remaining emissions (including non-CO_2 not covered in this paper) in the second half of the century as prescribed by Article 4.1 of the Paris Agreement. Technologies like direct air capture and enhanced weathering would need to be considered. Additional research is also needed to assess the sink potential of the forestry sector in Finland.

This paper is a first attempt to bridge "first-best" scenarios from IAMs (under idealised conditions) with real-world developments at the country level, by incorporating physical constraints, current policies in place, and other long term strategies or Sustainable Development Goals. SIAMESE allows for simultaneous downscaling of multiple countries and it can be employed to assess possible inconsistencies between regional IAM pathways and other long term goals at the country level. This could provide valuable information to both policy makers (on the need to update policies in line with 1.5C) and the IAMs community (to better reflect country-specific circumstances in their models) Another interesting feature of SIAMESE (not explored in this paper) is the possibility to "deviate" from the boundaries conditions of IAMs, in case of newly adopted policies at the country level which were not anticipated by older IAMs scenarios. In this case SIAMESE could provide an estimate of the impact of newly adopted policies at the country level on global emissions pathways.

Finally, SIAMESE is a reduced complexity IAMs which conceptually mimics IAMs at finer geographical resolution scales. However, SIAMESE has been designed for downscaling results from any energy-system economic model, for example including the World Energy System model (employed in the IEA/OECD World Energy Outlook series) or ETP/TIMES (IEA Energy Technology Perspective series), or other national models for sub-national emissions analysis.

SIAMESE does not explicitly model the energy extraction side nor trade across countries. For this reason, we were not able to take into account policies aiming at increasing the energy self-sufficiency ratio in Finland (e.g. by reducing the amount of imported oil). Similarly, the absence of carbon trade across countries narrows down the field of application of SIAMESE. For example, SIAMESE cannot deliver a “limited CCS scenario” in Finland, unless such scenario is available from IAMs for the broader (e.g. WEU) region[10]. Future research might expand our model to include trade of carbon credits and a detailed representation of the energy production side.

This paper has focused on aggregated primary energy demand and CO_2 emissions (excluding LULUCF) in Finland. A limitation of this study is the lack of a detailed analysis at the sectorial level, including the electricity, buildings, transport and industry sectors. Such analysis would be needed to identify key technologies in different sectors and policies to deploy them at scale. Certainly, it would be also interesting to analyse the implications of the Paris Agreement for the energy sector and carbon budgets of other key countries and this will guide our future work.

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[10] If we were to run such scenario, based on a “full technology” scenario for the WEU region, SIAMESE would reallocate emissions from Finland to the rest of WEU countries, without considering the need for additional mitigation measures in Finland (e.g. earlier phase out of fossil fuels) to avoid costly carbon credits compensations

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Appendix A

SIAMESE mimics the structure of IAMs, in which the economic output (GDP) is a function of capital, labour and energy consumption, by using a nested CES (Constant Elasticity of Substitution) production function. The basic idea behind the CES production function is that it would be possible (at increasing cost), to replace one factor of production with another (e.g., capital with energy consumption).

The CES (constant elasticity of substitution) production function can be represented as follows:

$$Y_{t,j} = \gamma_{t,j}\left\{a_j\left(K_{t,j}{}^{s}L^{1-s}{}_{t,j}\right)^{\rho} + (1-a_j)\left[\left(\sum_f a_{j,f}Q_{t,j,f}{}^{1/\rho_e}\right)^{\rho_e}\right]^{\rho}\right\}^{1/\rho} \qquad \text{(A.1)}$$

Here, Y is the output (GDP) variable for each region *j* and time period *t*. To avoid a cumbersome notation, equation (A.1) represents only the first two nests of the CES production function. The first nest involves the substitution between combined capital K and labour L with energy Q. The parameters are: γ is the total factor productivity, a_j represent the share between combined capital and labour (*K* and *L* respectively) and energy *Q*, and ρ represent output elasticities in the reciprocal form – elasticity of substitution = 1/(1- ρ). The second nest involves the substitution of energy Q across different fuels *f* with output elasticity ρ_e and fuel shares $a_{j,f}$. For the third nest – substitution across fuels with and w/o CCS (Carbon Capture and Storage) – we assume a high elasticity of substitution (equal to 20), which is roughly in line with standard IAMs assumptions[11].

In order to provide realistic results, we harmonise the GDP with external projections by calibrating γ. The parameter γ is exogenous and it can be interpreted as a proxy of technological progress.

[11] IAMs typically assume an infinite elasticity of substitution for CCS technologies. SIAMESE instead employs a high – although not infinite – elasticity of substitution. Indeed, an infinite elasticity of substitution (e.g. a linear model) would entail the same marginal cost for both CCS and non-CCS technologies. This could lead to problems in the allocation of energy resources, which is driven by the marginal cost of energy.

The inputs to the CES utility function representing GDP are labour *L*, capital *K*, and energy consumption *Q*. The latter consists of six main fuels *f*: coal, oil, gas, nuclear, biomass, and non-biomass renewables. Coal, Gas and biomass are further decomposed into CCS (Carbon Capture and Storage) and w/o CCS technologies.

Production of goods by capital and labour is represented by a Cobb-Douglas production function (elasticity of substitution equal to one).

The capital evolution *K* is determined by the depreciation rate δ and the investment *I* that have been made since the previous time step.

$$K_{t+1,j} = K_{t,j}(1 - \delta)^{\Delta t} + I_{t,j}\,\Delta t \qquad \text{(A.2)}$$

Consumption of final goods is the remainder of the GDP after subtracting investment and energy expenditures:

$$C_{t,j} = Y_{t,j} - I_{t,j} - \sum_{f} Q_{t,f}\; P_{t,f} \qquad \text{(A.3)}$$

The SIAMESE model is driven by the boundaries from a given IAM scenario (e.g. MESSAGE 2C or 1.5C). To this end, we assume that the sum of all energy consumption allocated to the country level needs to be equal to the total sum for the broader region ($\bar{Q}_{f,t}$), which is an input to SIAMESE (Equation A.4 – this can be also seen as a market clearing condition).

$$\sum_{f} Q_{f,j,t} = \bar{Q}_{f,t} \qquad \text{(A.4)}$$

Like other IAMs, SIAMESE assumes perfect energy markets (Edenhofer et al. 2010, Massetti and Sferra 2010, Huntington et al. 2013), where energy prices coincide with marginal costs. As a result, we compute the energy prices as the derivative of GDP with respect to energy consumption (marginal utility of energy), as in Equation A.5 [12]. In other words, since SIAMESE provides a cost-optimal solution (under a welfare maximisation approach), there is always (all other things being equal) a monotonic relationship between a given energy price and the "optimal" energy consumption level (for each fuel and time period). As we already know the energy consumption data from regional IAM data, we let the SIAMESE model find the energy prices associated with that energy consumption level.

$$\frac{\partial Y_{j,t}}{\partial Q_{j,f,t}} = P_{f,t} \qquad \text{(A.5)}$$

In the "Standard version" of SIAMESE - with uniform policies across countries - the latter constraint needs to be fulfilled for all countries equally. Finally, SIAMESE allocates energy consumption (and emissions) from regional IAM data to the country level based on those energy prices and the GDP and population assumptions (in line with SSP storylines) (from Equation A.1). In this paper, we use the "Standard version" of SIAMESE to validate the model results against historical data (section 4).

For future scenarios (Section 5), we enhance SIAMESE by introducing country specific policies (e.g. coal phase out in Finland) as well as geophysical constraints (e.g. carbon capture sequestration and storage potential)[13].

Finally, the objective function for the time-dependent solution is represented in Equation A.6:

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12 Please note that under stabilisation scenarios, energy prices embed a "shadow" price of carbon (only for fuels containing carbon).

13 From a model perspective, introducing country-specific constraints on energy consumption (such as banning coal use), leads to an allocation of resources that is no longer "optimal" (e.g. same marginal costs across countries). In other words, it is not possible to equalize the marginal cost (utility) of energy across countries (as in equation A.5), unless energy is a "free" (unconstrained) variable in the optimization process. For example, an earlier phase out of coal in Finland would entail a higher marginal cost (as defined in equation A.5) compared to the rest of WEU region (driven by a higher "shadow" price of carbon for coal). Therefore, while introducing country-specific constraints we relax equation A.5 and use "exogenous" energy prices, based on the results of the Standard version of SIAMESE.

$$W = \sum_{t,j} (1 - d)^t \; L_{t,j} \log \frac{C_{t,j}}{L_{t,j}} \qquad \text{(A.6)}$$

W is the welfare to be maximised. The model parameters for the first year, i.e., the static solution, and the time-dependent solution are obtained with a two-step calibration approach:

1. Static calibration: finds shares a and a_f, and initial γ (Total Factor Productivity at the base year).
2. Dynamic calibration: finds the Total Factor Productivity values over time to match external GDP projections.[14]

Static Calibration

We calibrate SIAMESE to match the observed data for GDP and energy consumption in the base year (for each fuel). To do so, we find the shares of the factor of production a_j, $a_{j,f}$ as well as γ_j based on the observed data at the base year, by imposing the derivative of the utility production function of GDP with respect to capital K to be equal to the sum of interest i and depreciation rate δ. At the same time, the derivative of GDP with respect to energy consumption needs to be equal to the price p_f.

$$\frac{\partial Y_j}{\partial K_j} = i + \delta \qquad \text{(A.7)}$$

$$\frac{\partial Y_j}{\partial Q_{j,f}} = P_f \qquad \text{(A.8)}$$

Finally, the shares between different inputs should sum up to one:

[14] On the one hand we use GDP projections from MESSAGE for the WEU region. On the other hand, we rely on SSP2 data (Fricko et al.2016) at the country level to harmonise Finland's GDP projections (Source: SSP database).

$$\sum_f a_{f,j} = 1 \quad with \quad a_{f,j} \in [0,1] \qquad \text{(A.9)}$$

For CCS technologies, we use a slightly different approach. In this case, instead of calibrating the shares of the CES function based on the observed data[15], we assume a fixed value ($a_{j,f}$ equal to 50%). At the same time, we assume an arbitrarily small value for CCS consumption in WEU region at the base year (0.01 EJ/yr). As a result, the CCS shares within fuel will be the same across all countries. In the standard version of SIAMESE (with endogenous price), this condition holds true not only at the base year, but also dynamically over time.

Dynamic Calibration

GDP is an endogenous variable of SIAMESE. One key driver of the GDP is γ (the total factor productivity). In the dynamic calibration process, we calibrate γ in order to harmonise the GDP with authoritative (external) projections at the country level (e.g. SSP – Shared Socio-Economic Pathway scenarios, Fricko et al. 2016). To do so we change the γ_t while minimising the error (f_t) as in equation (A.10):

$$f_t = \sum_j \left(Y_{t,j} - \bar{Y}_{t,j}\right)^2 \qquad \text{(A.10)}$$

The iteration process stops when the error (f), for each time period t, is below a reasonably small threshold.

[15] There are virtually no large-scale CCS plants installed in Europe to date.

Appendix B

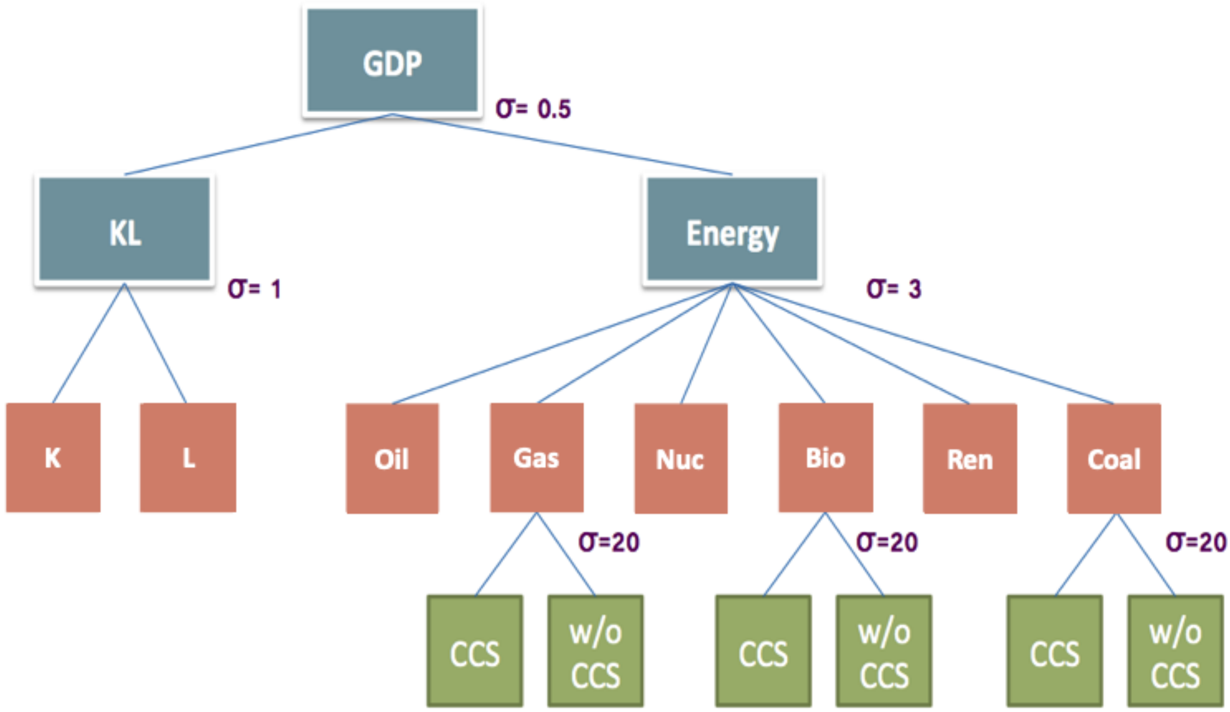


Figure B.1: Production function of SIAMESE.

SIAMESE assumes a CES (Constant Elasticity of Substitution) production function, where the GDP is a function of Capital (*K*), Labour (*L*) and Energy consumption (*Q*). Energy comprises six main fuels: Oil, gas, nuclear, biomass, new-renewables and coal. Gas, coal and biomass are further decomposed into CCS (Carbon Capture and Storage) and without CCS technologies.

Fuel	Carbon content (tC/TJ)
Coal	27.6
Oil	20.6
Gas	15.3

Biomass	29.9

Table B.1: Emission factors of fuels

We compute CO_2 emissions from energy and industry based on the carbon content of fuels[16]. SIAMESE uses emission factors in line with IPCC 1996 guidelines and the MESSAGE-GLOBIOM 1.0 documentation (Krey et al. 2016). Like the IAM MESSAGE, SIAMESE considers biomass as being carbon neutral in the energy system. Therefore, the carbon content of biomass is relevant only when biomass is coupled with CCS (Carbon Capture and Storage) technologies (Krey et al. 2016). The sequestration rate of CCS technologies is set at 90%, in line with MESSAGE model assumptions.

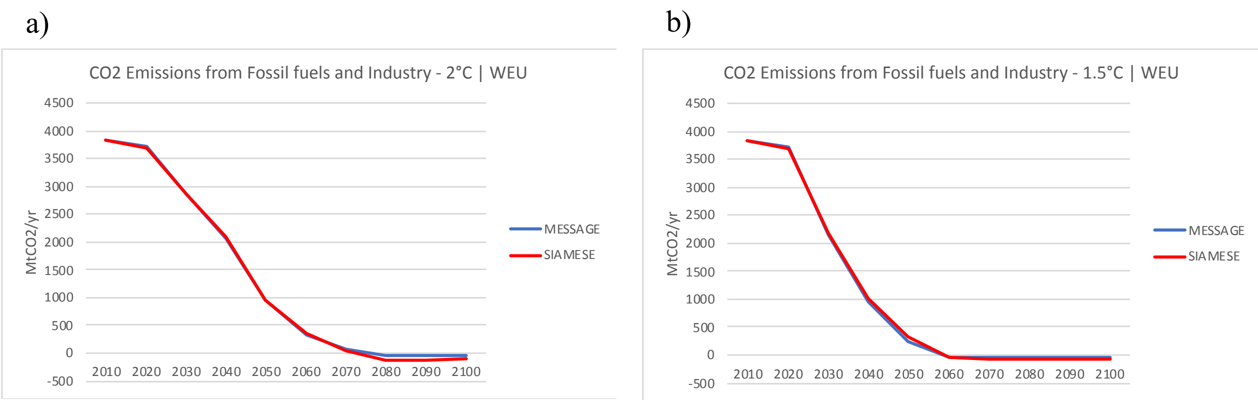


Figure B.2: CO_2 emissions from energy and industry (excluding LULUCF): SIAMESE (red lines) vs MESSAGE (blue lines). A comparison for the WEU region under a 2°C (a) and 1.5°C emission pathways (b).

Figure B.2 shows a good level of agreement between MESSAGE and SIAMESE, regarding CO_2 emissions from energy and industry for the Western European (WEU) region.

16 In this paper we assume that emissions from fossil fuels and industry can be entirely associated to the carbon intensiveness of the energy mix (by using emission factors by fuel). Figure A.2 shows that this assumption works reasonably well for the WEU region.

WEU (Western European) countries:	
Andorra	Ireland
Austria	Isle of Man
Azores	Italy
Belgium	Liechtenstein
Canary Islands	Luxembourg
Channel Islands	Madeira
Cyprus	Malta
Denmark	Monaco
Faeroe Islands	Netherlands
Finland	Norway
France	Portugal
Germany	Spain
Gibraltar	Sweden
Greece	Switzerland
Greenland	Turkey
Iceland	United Kingdom

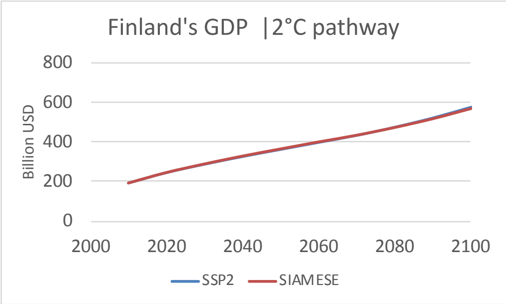
Table B.2: Countries of the WEU region (Source: MESSAGE model description)

time	GDP	Population
	% of total WEU	*% of total WEU*
2010	1.2%	1.1%
2020	1.3%	1.1%
2030	1.3%	1.1%
2040	1.3%	1.1%
2050	1.3%	1.1%
2060	1.3%	1.1%
2070	1.3%	1.2%
2080	1.3%	1.2%
2090	1.3%	1.2%
2100	1.4%	1.3%

Table B.3: Finland's Socioeconomic assumptions. Percentage share of Finnish GDP and Population with respect to the aggregated WEU region. Assumptions are based on SSP2 "Middle of the road" scenario (Source: SSP database, Fricko et al. 2016).

Table B.3 shows the main socio-economic assumptions for Finland, as percentage share of the WEU region. SIAMESE considers population as an exogenous variable. GDP instead is an endogenous variable. Therefore, we use the SSP2 data (shown in table B.3) as target values in the GDP calibration process (as described in Appendix A, dynamic calibration). Figure B.3 shows the fit of the calibration of Finland's GDP under a 2°C and 1.5°C pathway.

a) b)



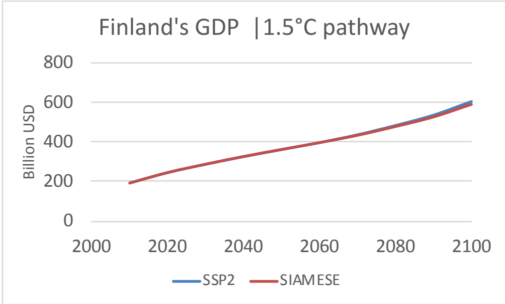


Figure B.3: Dynamic calibration of GDP over the 21st century. Comparison between SSP2 assumptions (blue lines) and SIAMESE simulations (red lines) under a 2°C pathway (a) and 1.5°C pathway (b).

Symbol	Description	Value
δ	Depreciation rate of capital (per year)	3%
d	Pure rate of time preference (per year)	3%
i	Interest rate (per year) of capital for base year calibration	5%
ρ	Reciprocal of the elasticity of substitution (σ), upper nest	-1
ρ_e	Reciprocal of the elasticity of substitution (σ), energy nest	0.667
ρ_c	Reciprocal of the elasticity of substitution (σ), CCS nest	0.95

Table B.4: Main SIAMESE model Parameters.

Appendix C

This appendix shows the SIAMESE primary energy consumption (by fuel) for Turkey during the historical period 1970-2015.

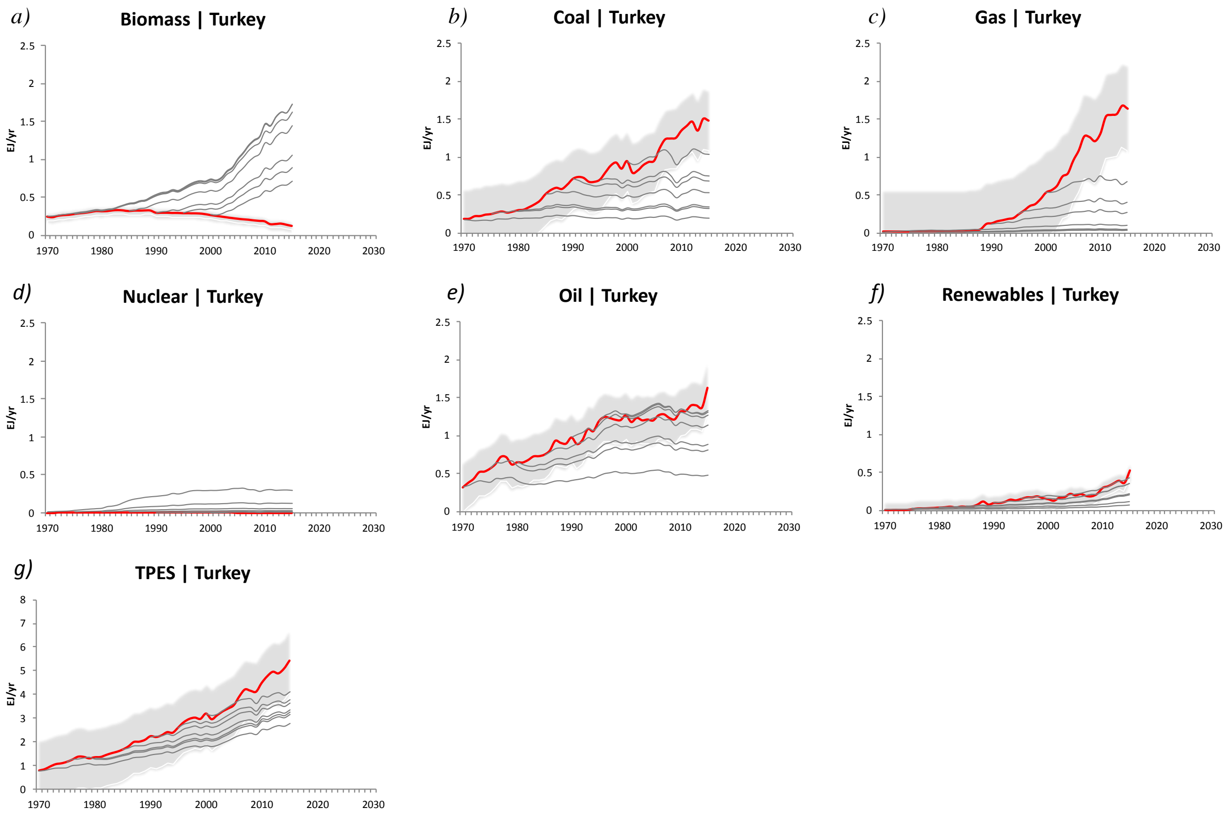


Figure C.1: SIAMESE model vs observed data. A red line depicts the historical data for each fuel: biomass (a), coal (b), gas (c), nuclear (d), oil (e) and renewables (f) as well as the Total Primary Energy Supply (g), source: IEA 2016. The light grey range represents the historical volatility of data (+/- one standard deviation). Grey lines represent simulations from SIAMESE starting from different base years: 1970, 1975,1980, 1985, 1990, 1995 and 2000.

Figure C.1 shows that the assumption of uniform policies across all countries does not work so well for Turkey over the historical period 1970-2015. Those results were largely expected for a country like Turkey as it is a developing country outside the EU28 (with no legally binding obligations under the Kyoto Protocol).

Past policies had a key impact on the energy market in Turkey, leading natural gas to become the "preferred choice" for fueling a huge amount of new power plants additions during the last decades, also because of its proximity with gas exporter countries (Hacisalihoglu 2008). The liberalization process of the gas market started in 2001, aiming at a better harmonization with the EU legislation although it is far from being completed (IEA 2009, IEA 2016).

In a context of Paris Agreement compatible pathways over the 21st century, we argue that the assumption of "harmonised" policies across countries makes a lot of sense, as all countries need to converge to low carbon policies. At the same time, we recognise the need to reflect specific national circumstances as we did for Finland. In this context, SIAMESE can provide valuable information on how to improve the NDC targets and long term goals at the country level, in line with the objective of the Paris Agreement as well as other national targets.

*Highlights

Highlights

- We downscale regional IAMs results to the country level with a new model: SIAMESE
- Results over the historical period confirm the validity of our approach
- Using Finland as an example, we analyse CO2 emissions for both 1.5°C and 2°C pathways.
- We calculate the remaining carbon budget until mid-century and 2100 for the example case of Finland.