Benchmarking local network topology of sustainable heat supply: An open-source approach downscaling integrated assessment model results

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Abstract

Aiming towards sustainable heat supply for residential/commercial buildings implies the necessity of decarbonizing heat production portfolios. Most decarbonization studies examine net-zero scenarios on a highly aggregated level using integrated assessment models (IAMs) with global coverage. To translate these high-level transformation pathways to policy measures at a local resolution, it is necessary to downscale results from an aggregated level to a higher granularity. This work's core objective is to examine the local network topology of sustainable heat supply and to identify the trade-offs for heat supply companies between low-carbon energy carriers, a significant heat demand reduction by building renovation, and a heat network expansion integrating renewable technologies such as geothermal and green gas high-efficiently. A two-stage analysis is proposed, including a downscaling algorithm for using IAM results for obtaining high spatial granularity using a novel downscaling technique accounting for the infrastructure requirements of centralized heat supply options and population density as criteria, and a benchmarking assessing network-based heat supply topologies. Using Austria as a case study, we downscale values projected by different decarbonization storylines from the H2020 openENTRANCE

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project. Results indicate that sustainable heat networks achieve only lower heat densities compared to existing networks, thus reducing infrastructure to supply ratio efficiency.
Keywords:

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1. Introduction

- Which downscaling method for the energy technology generation comes closer to predicting the nodal heat demand in the residential and commercial sector accounting for energy technologies' infrastructure needs on a high spatial granularity?
- What, if any, is the impact of using such downscaling methods to dissaggregating the nodal heat demand on benchmarking network-based heat service provision focusing in particular on the district heating network?

have displayed good simulation performance based on the large scale features and patterns of synoptic activities, but they are unable to capture the meso-scale and micro-scale physical processes that influence local climate variables. the simulation suffer substantial from bias in specific and detailed regions to bridge this spatial gap

terms of statistical downscaling methods, the empirical relation ships between large-scale low-resolution climate variables (pre dictors) and local high-resolution parameters (predictands) in a particular domain are established using statistical approaches, and then applied to GCM outputs [41]. Due to the advantages of easy implementation, fast computing speed, and low time consumption, statistical downscaling methods are widely used in climate change projections, in which large numbers of GCMs with various sce narios are often considered [42,43].

2. State-of-the-art and progress beyond

2.1. Verschiedene Arten des Downscaling, nicht nur empirisch

2.2. Downscaling integrated assessment model results

2.3. Assessing network-based technology potentials

2.4. Network/grid/infrastrucuture requirements in sustainable energy systems

3. Methodology

This section aims to describe the proposed approach to transform aggregated quantities of heat generation per technology to local heat network infrastructure topologies. The presented approach can be seen as a novel downscaling technique and is made, in particular, by two sequencing algorithms. Thereby, tailor-made indicators play a crucial role and serve as termination criteria for the downscaling process. Figure 1 illustrates the proposed idea to obtain local heat network topologies from IAM results. Thereby, *Algorithm1* transforms heat generation per technology from the region level (e.g., country) to the sub-region level (e.g., NUTS3) taking into account empirical settings for network infrastructure requirements of heat technologies on the sub-region level. Afterwards, *Algorithm2* disaggregates the results from the sub-region level to the small sub-region level (LAU) to obtain local heat networks and improve their network topology. The iterative application of the latter algorithm enables an improvement of the network topology by each iteration using a benchmarking with tailor-made indicators and leads to the local heat network topologies.

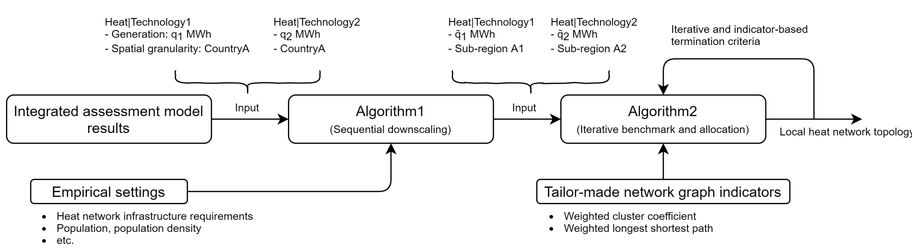

Figure 1: Basic concept of the downscaling technique using two sequencing algorithms

3.1. *Algorithm1: Sequential downscaling disaggregating heat generation per technology from the region to the sub-region level*

Here, we describe the technique to downscale IAM results of the low temperature residential and commercial heating sector from the region (NUTS0) to the sub-region (NUTS3) level.[1] The idea of *Algorithm1* is to extend the well-known linear downscaling technique, which essentially takes into account a single proxy as the downscaling driver. The linear approach distributes the value to be downscaled linearly in respect to the distribution of the proxy. This has often proven successful in many fields of application. However, in particular, the specific investigation of heat generation per technology of the low temperature heating sector reveals a lack of the default linear downscaling method. Without any further adaption of this methodology, there would be an impracticable disaggregation of heat generation per technology across all sub-regions. This might lead to the fact that strongly grid infrastructure-dependent heat generation technologies provide low temperature heat in very sparsly populated sub-regions as a result of their small share in the proxy. At the same time, however, it might be assumed that heat network infrastructure is being only provided in areas with sufficient heat densities since only these areas represent profitable business models for network-based low-temperature heat supply and heat supply companies.[2]. In this work, the idea of sufficient heat densities is adapted by using population density as the criteria for potentials of areas with network-based heat supply instead. There are esentially two main points for involving population density values as criteria. On the one hand, since population has established itself as the key proxy and downscaling driver along with GDP in the energy sector, the extension by population density seems to be consistent and the logical next step when focusing on spatial downscaling. On the other hand, the emprical data on the development of the population and thus on population density are often very well accessable and available. Furthermore, and this is especially the case for the analysis and empirical setting presented

[1]In principle, different tuples of spatial granularity between the spatial level of values to be downscaled and the desired spatial level of disaggregation could be analyzed using our presented technique.

[2]This is also demonstrated by the open-source toolbox (`https://www.hotmaps.eu/map`) developed in the European H2020 project *Hotmaps*. On the interactive platform, one can find feasible areas for district heating networks on a high spatial granularity by selecting a specific heat density as threshold criteria and thus filtering out areas with insufficient heat density values.

here, the values to be downscaled themeselves often implicitly include development/projections regarding heat demand and heat density (and thus can be seen to a certain extent inherent with IAM results). Algorithm 1 presents the sequential linear downscaling algorithm and each step from the IAM results to the heat generation per technology on the sub-region level.

Algorithm 1: Sequential linear downscaling algorithm

t: Heat generation technology supplying heat service needs ($t \in T$);
r: Sub-region (NUTS 3) within a country ($r \in R$);

input : Heat generation per technology on a country level obtained from IAMs: (q_t);
Population density per region r (ρ_r);
Total population per region r (p_r);
Heat network infrastructure requirement of t (σ_t);
Potential of heat network infrastructure at r (π_r);

output: Heat generation per technology on a sub-region level ($\hat{q}_{t,r}$);

Initialization:
Sort elements t in T descending by σ_t;
$q_r^{heat} \longleftarrow \sum_t q_t \cdot \frac{p_r}{\sum_r p_r}$; `// Downscale heat demand by population as proxy`
$\tilde{q}_t \longleftarrow q_t$; `// Available heat generation per technology t`

begin
    foreach t **do**
        $List = []$; `// Collect sub-regions that fulfill criterias`
        $demand = 0$; `// Used to disaggregate heat generation`
        $R' = R \setminus \{\forall r \in R : \pi_r \leq \sigma_t\}$; `// Filter sub-regions by criteria`
        foreach $r' \in R'$ **do**
            if $q_r^{heat} \geq 0$ **then**
                $List = List \cup r'$; `// Sub-regions that fulfill all criterias`
                $demand \mathrel{+}= q_r^{heat}$; `// Total demand of the sub-regions`
            end
        end
        foreach $l \in List$ **do**
            $\hat{q}_{t,r} = \frac{q_r^{heat}}{demand} \cdot \tilde{q}_t$; `// Heat technology generation at sub-region`
            $q_r^{heat} \mathrel{-}= \hat{q}_{t,r}$; `// Reduce heat demand at r`
        end
    end
end

In descending order of network infrastructure requirement, the heat generation technologies are iterated (line 5 and initialization). All sub-regions are collected that fulfill the heat network infrastructure requirements of technology t (line 8). Then, those sub-regions with zero heat demand (e.g., as a result of the supply by other heat generation technologies and the sequential process) are not further pursued and removed from the collection of sub-regions (line 10 and 11). The total heat demand of all sub-regions that fulfill all criterias and provide proper settings (line 12) are used to disaggregate heat generation to the sub-regions accounting for the individual heat demand (line 16). Finally, the heat demand at the sub-region is reduced to ensure that the total demand is covered by the heat generation technologies.

3.2. Algorithm2: Iterative heat network benchmark and heat generation allocation on the small sub-region level

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Algorithm 2: Iterative benchmark and disaggregation algorithm

s: Stage of iteration ($s \in \{0, 1, *\}$);
G^s: Heat network graph at stage s;
N^s: List of nodes at stage s: ($n^s \in N^s$);
L^s: List of lines connecting nodes k and j at stage s: ($l^s_{k,j} \in L^s$);
Q^s: Centralized heat generation at stage s: ($q^s_{n^s} \in Q^s$);
$\tilde{Q}^s$: On-site heat generation at stage s: ($\tilde{q}^s_{n^s} \in \tilde{Q}^s$);
Π^s: Benchmark indicator values at stage s ($\pi^s_{n^s} \in \Pi^s$);

input : $G^0 = \{N^0, L^0, Q^0, \tilde{Q^0}\}$;
output: $G^* = \{N^*, L^*, Q^*, \tilde{Q^*}\}$;

Initialization:
$s = 0$, $iter = True$;

begin
    while $iter = True$ **do**
        foreach $n \in N^s$ **do**
            $\Pi^s_{n^s} = f(N^s, L^s, Q^s)$; // Calculate indicator values
        end
        i with $\pi^s_i = min(\Pi^s)$; // Get index with lowest indicator value
        $N^{s+1} = N^s \setminus i$; // Remove index from list to obtain next stage
        $\tilde{q} = \sum_{N^{s+1}} \tilde{q}^s_{n^s}$; // Remaning on-site heat generation
        if $\tilde{q} \geq q^s_i$ **then**
            pass
        else
            $\tilde{q} = q^s_i$; // Limit quantity of centralized heat generation
        end
        foreach n^{s+1} **do**
            $q^{s+1}_{n^{s+1}} = q^s_{n^s} + \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; // Increase centralized heat generation
            $\tilde{q}^{s+1}_{n^{s+1}} = \tilde{q}^s_{n^s} - \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; // Decrease on-site heat generation
        end
        $L^{s+1} = L^s \setminus \{\forall l^s_{k,j} : k = i \vee j = i\}$; // Remove unavailable lines
        $G^{s+1} = \{N^{s+1}, L^{s+1}, Q^{s+1}, \tilde{Q^{s+1}}\}$; // Create new network graph
        $\Pi^{s+1}_{n^{s+1}} = f(N^{s+1}, L^{s+1}, Q^{s+1})$; // Calculate new indicator values
        if $mean(\Pi^{s+1}) \geq mean(\Pi^s)$ **then**
            $G^s = G^{s+1}$; // Set iteratively input network graph
        else
            $iterate = False$; // Stop iteration if no improvement
        end
    end
    $G^* = G^s$; // Set improved network graph as algorithm result
end

3.3. Definition of benchmarking indicators to assess heat network infrastructure topology

4. Results

5. Conclusions and outlook

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

References

Appendix A. Validation of the downscaled results on the NUTS3 level

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