Princeton's Net-Zero America study

Annex F: Integrated Transmission Line Mapping and Costing

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1 Introduction

Annex F describes the integrated process of mapping and costing a transmission line infrastructure that would a) allow the connection of the downscaled renewable resources sited in Annex D with the nearest selected Metropolitan Statistical Areas (MSAs), and b) allow approximate balancing of renewable energy flows between MSAs in order to ensure that each selected MSA has access to a minimum level of renewable electricity supply on an annualized basis. The Net Zero American Plan (NZAP) project team conducted integrated transmission mapping and costing for the base land availability case of the E+, E+ RE+, and E+RE- scenarios; for the constrained land availability case of the E+ scenario (see Annex D on land availability and solar and wind siting); and for the REF scenario. Figure 1 shows renewable resources sited under the base case of the E+ scenario. Annex F will use the base case of E+ scenario as its core case in discussing and illustrating the integrated process of mapping and costing transmission lines. Maps of high voltage transmission capacity additions supporting wind and solar generation for all modelled scenarios can be found in the Appendix to this annex.

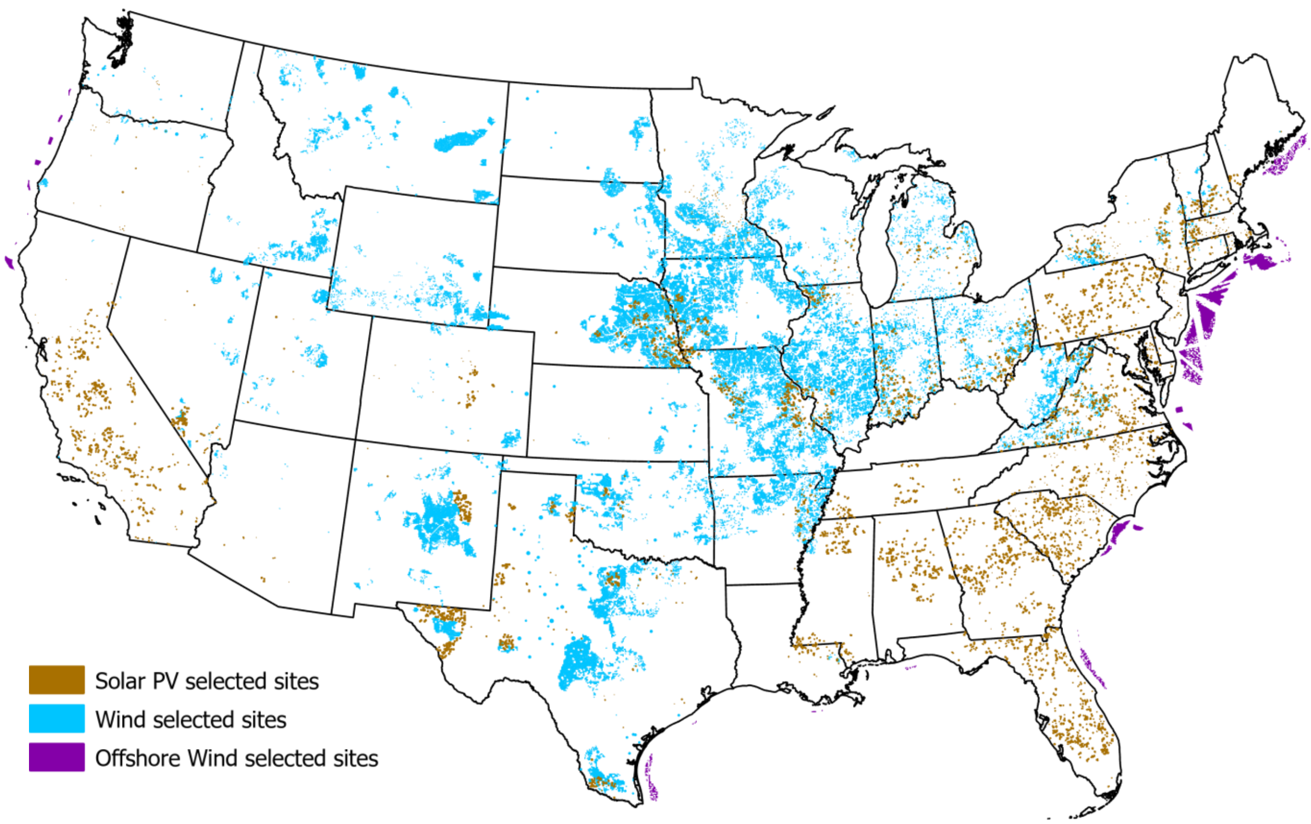


Figure 1 Selected wind and solar PV sites under the base case of the E+ scenario

In the first iteration of the project, the NZAP project team selected MSAs based on the 2020 population contained within an MSA's boundaries [1]. The minimum 2020 population of MSAs considered in the first iteration of the NZAP analysis is 750,000 people. The 74 MSAs shown in Figure 2 met this criterion.[1]

[1] Rochester, NY was inadvertently left out of the analysis, reducing the total MSAs in the analysis to 73.

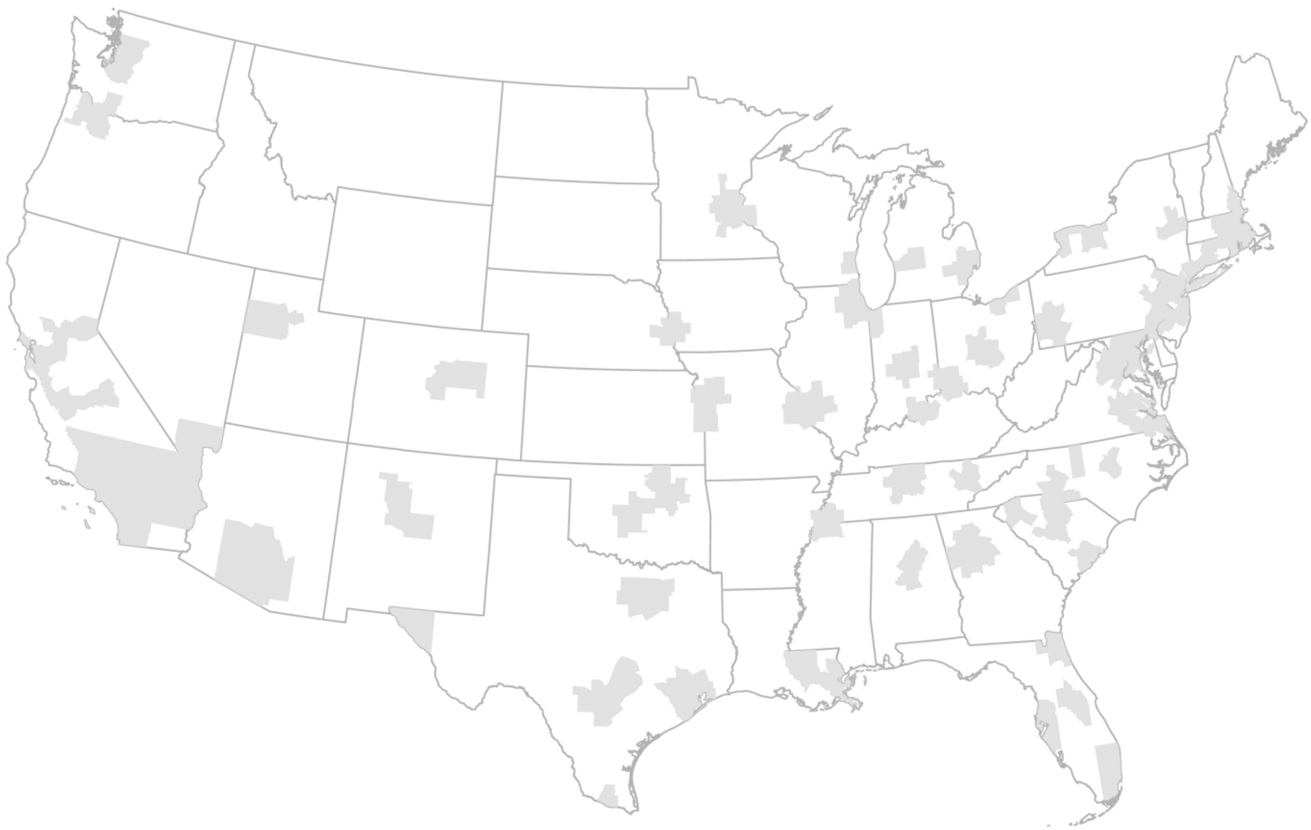


Figure 2 The 74 MSAs having a population greater than or equal to 750,000 people included in first iteration of NZAP

In order to estimate the total wind and solar energy supply required by each MSA, the NZAP team used the following steps:

A. Allocate the energy generated by the wind and solar sites selected in each scenario (see Appendix D) to each MSA after running a least cost transmission routing algorithm to find the least cost path between a project and all MSAs;
B. Determine regional demand from intermediate/flexible loads in RIO model outputs;
C. Determine regional renewable energy supply (wind and solar) from RIO model outputs, after removing annual curtailment (also in RIO model outputs), rooftop PV, and all pre-existing VRE – estimated as the RIO 2020 VRE build in the REF scenario;
D. Remove (B) demand from intermediate/flexible loads from (C) the regional renewable energy supply (wind and solar) in order to determine the bulk regional renewable supply;
E. Determine total regional generation from all sources by adding regional adjusted renewable generation (D) to generation from non-utility-VRE sources (thermal, hydro, rooftop PV), and adding/subtracting annual generation flows in/out of the region (via transmission);
F. Determine the share of total regional generation from renewables by dividing the bulk regional renewable supply (D) by the total regional generation (E);
G. Determine the regional final energy demand by subtracting regional demand from intermediate/flexible loads (B) and regional generation from all pre-existing VRE from regional final energy demand (from RIO model);
H. Allocate regional final energy demands (G) based on each MSA's share of the regional population [1];
I. Determine the amount of each MSA's demand to be supplied by new renewables by dividing each MSA's demand (H) by regional share of generation from renewables (F);

J. Subtract the demand to be supplied by new renewably energy for each MSA (G) in 2050 from the renewable energy delivered to each MSA (A) in 2050 in order to determine the amount of oversupply (positive number) or shortfall (negative number) of renewable generation supplied at each MSA;
K. Build MSA-to-MSA transmission (both within regions and across regions) to ensure that all MSA's left with a shortfall after step (J) have enough renewable generation to cover that shortfall. The capacity (MW) of each transmission line built to meet an MSA's generation shortfall (MWh) is found by:
    a. dividing the annual renewable generation transferred from an oversupply source by the number of hours in a year (8760 hours/ year) to get the average power generation transferred;
    b. dividing the generating capacity (K.a) by the average coincident capacity factor of wind and solar generation of 32% [Patankar et al. 2021 (forthcoming), "Land Use Trade-offs in Decarbonization of Electricity Generation in the American West" (in review)] to determine total wind and solar capacity necessary to deliver that average power generation;
    c. multiplying the result (K.b) by the maximum coincident capacity factor of wind and solar generation of 66% [Patankar et al. 2021] to determine the maximum coincident wind and solar capacity that the line must be capable of transferring.[2]
L. Check whether RIO inter-regional (IR) capacity builds are met either as part of above process, and after including all IR capacity additions occurring indirectly as part of spur line transmission builds
    a. if not, then build the additional transmission specified (in MW) between pairs of pre-selected MSAs in the regions specified

Annex F has four main sections. The first section details the process of mapping and costing transmission lines from the location of each sited wind or solar PV resource to the nearest substation, and then from that substation to the nearest MSA (if the substation is not already within an MSA's boundaries). Table 1 estimates transmission coverage for sited CPAs for each of the downscaled scenario/cases. The second section details both the process of balancing renewable resource capacity between MSAs, and the mapping and costing of transmission capacity to permit energy flows between MSAs (e.g. from those with oversupply to those with deficits). The third section discusses a method for determining the voltage classes and circuits of all transmission lines that were mapped and costed in the two prior sections. The fourth section compares downscaled transmission results with EER model results and GW-km projections from the NREL [2] 2012 Renewable Electricity Futures Study. A final section lists limitations of the NZAP transmission analysis and areas for further refinement and work.

[2] Summary equation: GWh / 8760 / 32% x 66% = GWh / 8760 x 2.0625. To further understand this method: Say the wind and solar resources using a line have an average capacity factor of 33%. To get X average GW of power you need 3x that total capacity. But the total capacity doesn't all produce at once, because it's a mix of wind and solar and at different locations that don't all peak at the same time. In fact, at highest, they produce at most 66% of combined capacity of all resources. In this case, one only needs a transmission line capable of carrying a max of 3x66% or 2x the average usage of the line.

Table 1 Estimate of % of wind and solar CPAs with sited transmission paths (by % of sited capacity in GW) for each of the downscaled scenario/case

Capacity	**E+ base**	**E+ constrained**	**RE+ base**	**RE- base**	**REF base**
New sited by NZAP (GW)	3,048	2,915	5,707	1,193	441
Have transmission (GW)	3,033	2,904	5,689	1,183	431
No transmission (GW)	15	11	18	10	10
Coverage of transmission (%)	99.51%	99.62%	99.69%	99.15%[3]	97.81%[4]

2 Integrated resource to metropolitan service area (MSA) mapping and costing

In this step of the process, we aimed to map the least cost pathway from each selected onshore and offshore renewable resource project site (candidate project areas or CPAs selected as per the process described in Annex D) to the nearest MSA. Table 2 provides an overview of the steps involved in this process. Table 10 lists the detailed steps involved in implementing this process in ArcGIS Pro [3] and R [4]. Table 3 summarizes the key parameters used in the integrated transmission mapping and costing model employed in this portion of the process.

Table 2 Overview of steps undertaken in the first iteration of integrated resource to metropolitan service area (MSA) mapping and costing

Step	**Description**
1. Clean renewable resource site data (solar PV, onshore wind, offshore wind)	Remove all existing EIA [5], [6] listed projects from transmission mapping analysis. Existing projects already have spur lines and are connected into the grid. transmission lines serving existing projects may be refurbished at a later date when existing projects are refurbished, but that is expected to occur as part of normal grid/project maintenance that is not explicitly part of the NZAP analysis. Remove all sites that have a sited capacity of zero.[5]
2. Clean and limit existing infrastructure data according to NZAP first iteration parameters (transmission lines, substations, MSAs)	NZAP cleaned substation data [7] to remove all entries that either provided no voltage rating, or which had a voltage rating of less than 161 kilovolts (kV).[6] Figure 5 shows those substations remaining after this step. NZAP then additionally cleaned substation infrastructure to retain only one substation in the dataset for each instance where two or more substations were within a 500 meter (m) straight line distance of each other.[7] MSAs [1] with a population of less than 750,000 were also removed from the first iteration of the analysis. In addition, if a selected MSA lacked a substation of 161 kV or greater, then NZAP placed a virtual 161 kV substation at the center of the MSA's bounding

[3] A lower coverage percentage occurred due to the removal of a number of EIA planned sites having the same center point from transmission mapping. Although these same sites were also removed from the RE+ scenario (see Table 11), the lower overall renewable resource build in the RE- scenario led to a lower coverage percentage.

[4] The reduction in renewable resources fielded led to many more longer bulk transmission lines (>483 km or 300 miles) between spur end points and MSAs falling below our critical threshold of 500MW. Thus these sites were no longer considered viable.

[5] A list of additional bad/problematic data flags that did not result in the removal of sited resources from the analysis can be found in Table 11.

[6] Transmission rights of way for 161 kV or greater lines typically exceed 100 feet width and are thus reasonable proxy for the width and routes that long distance transmission may take. See http://www.minnelectrans.com/transmission-system.html Additionally voltage levels below 161 kV are typically used for local high voltage distribution lines, not long distance transmission.

[7] Substations located within this distance of each other led to complications in the analysis due to NZAP's use of a 500 m by 500 m geospatial grid for the first iteration of site location and selection and transmission mapping.

Step	Description
	polygon.[8] NZAP also placed substations in offshore wind development regions to allow for aggregation of spur lines at an offshore transmission hub before being transmitted along an agreed on marine transmission corridor to a substation on land. At five onshore locations, we also added "collector" substations where the nearest existing substations were distant from renewable resource sites to avoid many parallel spur lines running in 'delta' like patterns to a distant substation. This was purely for cosmetic reasons to make maps render with less clutter and more realistic spur line routing. Figure 6 shows all substation locations considered in the NZAP analysis.
3. Create a differential cost surface to use in selecting the least cost pathway between each renewable resource and a substation (spur line)	NZAP developed the spur line cost surface shown in Figure 3 using costs found in NREL sources [8], [9]. Pre-inflation spur line costs per MW-mile are provided for reference in Table 13. NZAP incentivizes spur line connection along existing transmission corridors of any voltage level [10][9] shown in Figure 7 by decrementing the regional spur line cost by $50 along each corridor's length and width.[10]
4. Create a differential cost surface to use in selecting the least cost pathway between a substation connected to a spur line and MSA substations (transmission corridors) [11]	NZAP developed the long-distance transmission corridor cost surface shown in Figure 4 using NREL costs [8] . Pre-inflation transmission corridor costs per MW-mile are provided for reference in Table 14. NZAP incentivizes transmission connections along the 161 kV or greater transmission corridor network shown in Figure 8 by using the appropriate regional spur line costs in all areas outside of existing transmission corridors. Note that existing rights of way are used to approximate realistic distances and routes cognizant of topology and conflicting land uses, not to imply that all additional transmission lines will be sited on existing rights of way. While substantial increases in transfer capacity can be enabled by upgrading existing rights of way, many new routes will also need to be sited to accommodate the transmission infrastructure included in this downscaling.
5. Draw the least cost spur line connecting a renewable resource to a substation	For each renewable resource site on the map, draw the least cost spur line from the resource a substation. If the resource's footprint overlaps with a substation point, do not draw a spur line.
6. Draw the least cost transmission corridor connecting each substation identified in the prior step to a substation in an MSA	For each substation accessed by a spur line in the prior step in the map or overlapping with a renewable resource, draw the least cost transmission corridor from the substation to a substation in an MSA. If the accessed substation is already located within MSA boundaries, then do not draw a transmission corridor.
7. Clean spur lines and transmission corridors, and	Keep all spur lines of any length and capacity. Remove transmission corridors (and the resources they were implemented to transfer) from the transmission

[8] Three were added to MSAs in Texas. The first iteration of the analysis missing that Rochester, NY also lacks a substation with a rating of 161 kV or greater. This was caught at the end of the analysis and was not been corrected for in the first iteration. Rochester's proximity to Buffalo, NY – a renewable resource rich MSA which the capacity in all three downscaled scenarios to meet Rochester's need – suggests that an analysis that included Rochester, NY would have a minor impact on results.

[9] Spur lines are lower voltage and thus require narrower rights of way. We thus used all existing transmission rights of way as proxies for possible routes of spur lines accounting for relevant topologies.

[10] The $50/MW-km difference between existing transmission corridors and all other land-use types was chosen arbitrarily. The goal in creating the cost difference was to expediently preference connections that followed existing corridors, while minimizing deviation from the NREL based spur line costs in each region. A systematic sensitivity analysis or optimization would need to be run to determine whether a higher or lower cost difference might more efficiently achieve those dual goals.

[11] This nomenclature is introduced in this Annex in order to ease referral to these types of lines and differentiate them from both spur lines and long-distance transmission lines built in following sections to accomplish other goals.

Step	Description
estimate the capacity weighted cost and MW-km of each connection	analysis if the identified transmission corridor is **both** longer than 483 kilometers (km) and is designed to transfer less than 500 MW of aggregated solar PV and wind capacity. These lines are excluded as unrealistic sized to justify transmission over this long distance. This screening drops less than 0.15% of lines and thus does not affect the overall analysis. In order to get a total cost for each new transmission connection, a) sum the cost surface values of each km of the transmission connection, b) multiply that sum by the resource capacity being transferred by the connection, and c) add a transmission system tie in cost for the connection [11].

Table 3 Additional key parameters used in the integrated mapping and costing model

Key Parameter	Selected value	Source
Spatial analysis cell size	500 meters x 500 meters	NZAP
MSA population threshold	750,000 people (in 2020)	NZAP
Minimum substation voltage for inclusion in analysis	161 kV	NZAP
Minimum transmission corridor voltage to be used for spur line	None	NZAP
Minimum transmission corridor voltage to be used for long distance transmission	161 kV	NZAP
Maximum length allowed for transmission corridors transferring 500 MW or less of capacity to an MSA	483 km (300 miles)	NZAP
Transmission tie-in cost (inflated to USD2018/MW from source)	14,749 USD2018/MW	[11]

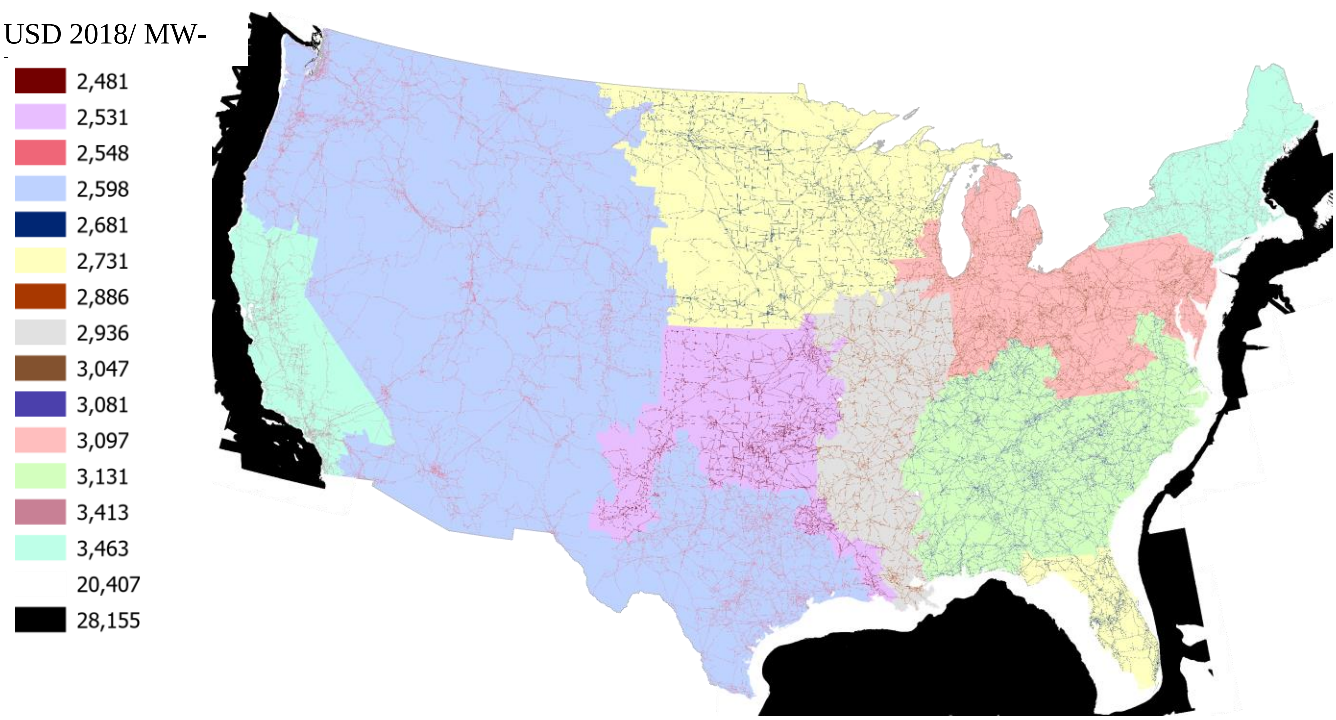


Figure 3 NZAP spur line cost surface in USD2018/MW-km[12]

[12] Far offshore areas, in which no turbines were built and in which no transmission is run, appear as white in the figure, but should not be correlated to a transmission cost in the key.

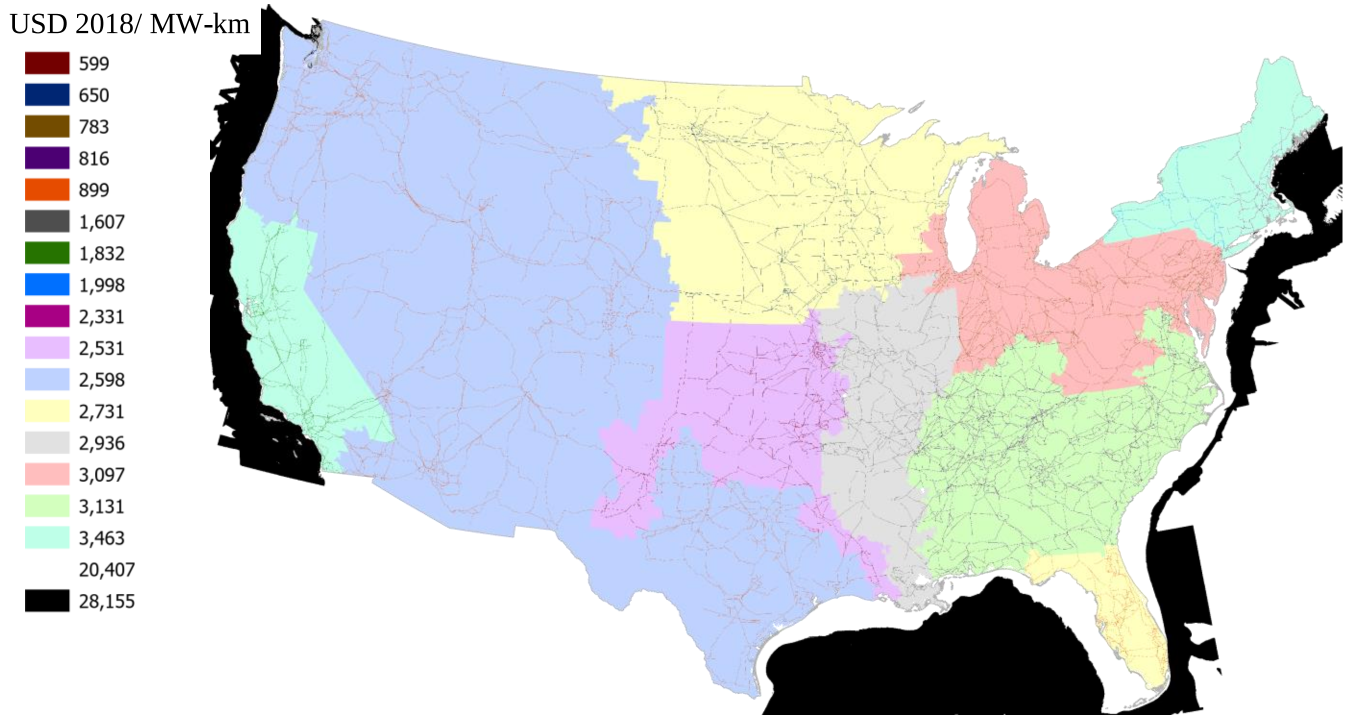


Figure 4 NZAP transmission line cost surface in USD2018/MW-km[13]

3 Balancing renewable resource capacity between MSAs, and MSA-to-MSA transmission mapping and costing

A first major step in the process involves building transmission between MSAs to fully cover the EER specified inter-regional transmission build. This capacity is selected endogenously by EER's least-cost optimization model RIO to provide sufficient transmission capacity to transfer energy between the 14 model regions and meet hourly electricity sector supply/demand balance constraints in all regions at least cost.

The second major step in this process involves building additional transmission between MSAs in order to ensure that each MSA has enough renewable generation to cover its regional allocation of renewably powered demand in 2050 (see steps A through J in Section 1) **Error! Reference source not found.**. This step is meant to approximate the intra-regional transmission capacities needed to ensure adequate supply of renewable electricity at all major metropolitan centers. As the spur lines and transmission lines connecting renewable project sites to MSAs connect to the nearest MSA, metropolitan areas close to large renewable energy supplies are over-supplied at the end of this step, while others further from renewables are under-supplied. This stage uses an optimization algorithm to expand intra-regional high voltage transmission lines from over-supplied MSAs to under-supplied MSA in need of additional renewable energy supply, until all MSAs are adequately supplied. The algorithm used in this step optimizes MSA-to-MSA connections by minimizing the cost of connections required to provide additional renewable energy supply to each MSA with a shortfall.

Table 4 provides an overview of the steps involved in the MSA-to-MSA transmission build processes. Table 12 lists the detailed steps involved in implementing this process in ArcGIS Pro [3], R [4] and Julia

[13] Ibid.

[12]. Table 5 summarizes the key parameters used in the integrated transmission mapping and costing model employed for MSA-to-MSA balancing and transmission builds.

Table 4 Overview of the steps involved in the MSA-to-MSA transmission build processes

Step	Description
1. Determine the inter-regional MSA-to-MSA transmission corridor builds needed to meet the EER model specified inter-regional transmission capacity in 2050	Determine the additional transmission capacity (if any) that needs to be built in order to meet EER model specified inter-regional transmission capacity for 2050. This is achieved by comparing the EER specified 2020 to 2050 inter-regional transmission build for each scenario with the inter-regional transmission builds occurring as part of cumulative 2020 – 2050 transmission corridors from renewable project locations sited by NZAP and the nearest MSA for each scenario/case in the prior section
2. Determine the MSA-to-MSA transmission needed to ensure each MSA in the analysis has access to the renewable generation needed to cover its regionally allocated demand to be supplied by new renewables in 2050	In order to determine the MSA-to-MSA transmission capacity that is required to transfer renewable generation to each MSA in the analysis with a renewable generation shortfall, the NZA team a) Estimated the least cost path (in USD2018 per MW) between MSAs (in all, the least cost paths of 182 MSA-to-MSA corridors was estimated) b) Determine the optimal MSA-to-MSA transmission configuration to minimize the total cost of transfer renewable generation to all MSAs in the analysis with a renewable generation shortfall
3. Draw the least cost pathway for each identified MSA-to-MSA transmission corridor	Draw the least cost inter-regional MSA-to-MSA transmission corridor between the MSAs closest to the specified corridor's border, and draw supporting MSA-to-MSA transmission corridors between specified MSAs.
4. Clean MSA-to-MSA transmission corridors, and estimate the capacity weighted cost and MW-km each corridor	Remove MSA-to-MSA transmission corridors from the transmission analysis if the corridor is **both** longer than 483 kilometers (km) and is designed to transfer less than 500 MW of aggregated renewable capacity. In order to get a total cost for each transmission line drawn in prior steps, a) sum the cost surface values of each km of the transmission line, b) multiply that sum by the resource capacity being transferred by the line.

Table 5 Key parameters used in the integrated transmission mapping and costing model used for MSA-to-MSA builds

Key Parameter	Selected value	Source
Spatial analysis cell size	500 meters x 500 meters	NZAP
MSA population threshold	750,000 people (in 2020)	NZAP
Minimum substation voltage for inclusion in analysis	161 kV	NZAP
Minimum transmission corridor voltage to be used for MSA-to-MSA transmission connections	161 kV	NZAP
Maximum length allowed for MSA-to-MSA transmission lines transferring 500 MW or less	483 km (300 miles)	NZAP

4 Determining voltage classes and circuits

NZAP considered voltage classes and circuits as an additional exercise to improve the integrated costing and mapping process discussed thus far. NREL figures [8], [9] used in the costing process assumed that all spur lines were 230 kV (and it is assumed single circuit), and that all long-distance transmission corridors were built at the highest voltage class (345 kV, 500 kV, 765 kV) pre-existing in any NREL costed region. NZAP imported those assumptions along with the NREL cost structure.[14]

NZAP's additional downscaling of transmission corridors into voltage classes and circuits serves two purposes. First, it allows NZAP downscaling to include the additional costs of corridors that would likely need to be high-voltage direct current (HVDC) rather than high-voltage alternating current (HVAC) in order to cover the required distance between transmission start and end points. Second, it details a more granular long-distance transmission build than allowed by NREL bins that only specify a single voltage class for each region. Table 6 details the transmission corridor characteristics used in determining HVDC build and adding the cost of HVDC converter stations to the corridor costs determined in prior sections – this table is aligned with NREL assumptions and NZAP costing method.

Table 6 Voltage class characteristics used in HVDC downscaling, modified from [13], [14]

Bin	Voltage class - action	MW min	MW max	Km min	Km max
(0) Remove	N/A - remove from transmission downscaling	0	500	483	N/A
(1) Spur	230 kV single circuit – no action taken	0	N/A	0	N/A
(2) Substation-to-MSA or MSA-to-MSA, < 300 miles	Use the NREL [8] assumed voltage (345 kV, 500 kV, or 765 kV) for each region – no action taken	0	N/A	0	483
(3) Substation-to-MSA or MSA-to-MSA, > 300 miles	HVDC – add NREL [8] HVDC converter station costs of 266,541 USD2018/MW (inflated from USD2015) to HVDC corridors	500	N/A	483	N/A

Table 7 details the transmission corridor characteristics used in further downscaling transmission corridors into voltage class and circuit estimates – these estimates are not reported as part of formal NZAP cost estimates but can aid readers in understanding the on-the-ground aspects of some of the larger corridors in NZAP results (e.g. number of circuits of what voltage level and thus what right of way dimensions).

Table 7 Voltage class characteristics used in informal voltage class and circuit downscaling of HVAC transmission corridors, modified from [13], [14]

Bin (see Table 7)	Voltage type	Voltage class	circuits	lines	Minimum MW	Maximum MW
2	HVAC	345 kV Single Circuit	1	1	0	400
2	HVAC	345 kV Double Circuit	2	1	400	800
2	HVAC	500 kV Single Circuit	1	1	800	900
2	HVAC	765 kV Single Circuit	1	1	900	2400
3	HVDC	500 kV Single Circuit	1	1	500	3500

In order to specify the lines and circuits in an HVAC corridor having a capacity of greater than 2400 MW in 2050, transmission downscaling divides the total corridor capacity by 2400 MW to determine the number of parallel 765 kV single circuit HVAC lines within the corridor. In order to specify the lines and circuits in an HVDC corridor specifying a capacity of greater than 3500 MW in 2050, transmission

[14] EER model costs are drawn from the same sources.

downscaling divides the total corridor capacity by 3500 MW to determine the number of parallel 500 kV single circuit HVDC lines within the corridor.[15]

For process illustration purposes, Table 15 presents transmission corridor characteristics for the E+ base scenario/case.

5 Comparing transmission results with NREL literature and EER costs

5.1 NREL study

Table 8 provides a comparison of key indicators from NZAP transmission downscaling and the 2012 NREL *Renewable Electricity Futures Study* [2].

Table 8 Comparison of key indicators from NZAP transmission downscaling for base cases and the 2012 NREL [2] Renewable Electricity Futures Study

Model	Renewable share of generation in 2050 % (only variable)	Total Demand (TWh) in 2050 – includes intermediate flexible loads	New transmission (GW-km)	New transmission / Existing transmission (proportion)	Total transmission / Total Demand (proportion)
NREL	90%	3,920	317,041	1.0	163/1
NZAP E+ base	89% (60)	9,717	672,869	2.1	102/1
NZAP RE+ base	100% (71)	15,819	1,308,971	4.1	103/1
NZAP RE- base	49% (35)	8,457	306,145	1.0	74/1
NZAP REF base	43% (39)	5,426	151,736	0.5	56/1

The annual and cumulative build-outs of total transmission infrastructure in NZAP scenario/cases in 2050 (in terms of % of multiples of the ~200,000 GW-miles or 321,869 GW-km reported as comprising the US transmission system in 2012 [2]) are as follows:

- The E+ base build of 672,869 cumulative GW-km is 418,101 GW-mi or ~2.1x the 2012 US transmission system.
- The RE+ base build of 1,308,971 GW-km is 813,357 GW-mi or ~4.1x the 2012 US transmission system.
- The RE- base build of 306,145 GW-km is 190,230 GW-mi or ~1.0x the 2012 US transmission system.
- The REF base build of 151,736 GW-km is 94,285 GW-mi or ~0.5 the 2012 US transmission system.

The NZAP transmission 2050 build-outs correspond to a national demand of approximately 9,717 TWh in the E+ scenario, 15,819 TWh in the RE+ scenario, 8,457 TWh of demand in the RE- scenario, and

[15] Upper bound voltage capacity threshold and voltage class inferred from current and planned HVDC project descriptions [15]–[17].

5,246 TWh of demand in the REF scenario. These demands can be compared with a demand of approximately 3,920 TWh in the reference NREL study [2]. NZAP total demands are 2.5x, 4x, 2.2x, and 1.4x the NREL study demand in E+, RE+, RE-, and REF scenarios respectively.

The reference NREL study [2] assumes 197,000 GW-miles of new transmission (inter- and and intra-regional) by 2050 for a 90% renewables scenario, or ~317,041 GW-km. If total GW-km are considered in proportion to each scenario/cases projected load in Table 8, then all NZAP scenarios have a much lower new transmission to demand proportion. This likely arises from the fact that the NREL study's projected load in 2050 is only 220 TWh larger than the reported end-use electricity demand of 3,700 TWh in 2008, and the study focuses on the decarbonization of just the electricity system rather than holistically considering all US emissions.

5.2 TX costs explicitly included in EER results

Table 9 provides a comparison of the explicit costs detailed in EER model outputs, with the costs arrived at after NZAP downscaling steps for base cases of E+, RE+, RE- and REF scenarios. The NZAP costs reported in Table 9 do not account for the replacement capital (or depreciation) needed to ensure the continuity of project delivery through the entire lifetime of the project (see Appendix M – Mobilizing capital for the transition).

Table 9 Comparison of the explicit costs detailed in EER model outputs, with the costs arrived at after NZAP downscaling steps for base cases of E+ and RE+

Model	E+ scenario (billion 2018USD)	RE+ scenario (billion 2018USD)	RE- scenario (billion 2018USD)	REF scenario (billion 2018USD)
EER costs (explicit in output)	1,114	1,950	429	216
NZAP costs (base case)	1,228	2,389	464	247

EER spur line transmission costs were arrived at by multiplying total sited solar PV/wind capacity (capacity.csv) by EER provided spur costs for each resource type (NEW_TECH_TX_COST.csv). Costs for all EER long-distance transmission lines were arrived at by multiplying 2050 inter-regional corridor capacities (total_transmission_capacity.csv) by the EER provided transmission corridor upgrade costs (TRANSMISSION_CAPITAL_COST.csv). The total EER transmission costs shown in Table 9 represent the sum of those two estimations.

NZAP costs are likely higher because the EER model does not explicitly track the general transmission wide upgrades occurring within each EER region after new spur lines are connected to existing transmission infrastructure. No effort has been made to separate the revenue requirements arising from regional transmission upgrades from other EER reported costs and include in transmission costing. This lack may be partially balanced by lowered NZAP costs resulting from NZAP's use of spur lines crossing regional borders to partly/fully fulfill EER specified intra-regional transmission corridor build/upgrades (negating the need to build them).

6 Limitations and further work

We have identified the following limitations in the NZAP transmission analysis. Areas for further refinement are noted where applicable.

1. Transmission capacity sizing assumes a simple coincidence factor between solar and wind projects connected to each line. No hourly modelling of actual variation in wind and solar generation or co-optimizing of line capacity and renewable capacity and operations is explicitly performed, except for the inter-regional transmission capacity estimated endogenously by EER's RIO model. Transmission capacities should thus be considered approximate, and future work would require optimal power flow analysis to ensure adequate transfer capacities between all buses in the real power system.
    a. Similarly, there may be additional transmission capacity that yields net cost savings by enabling geographic aggregation of time variant demand and wind, solar, and hydropower availability across larger geographic areas. Determining this additional capacity would require running a power system optimization model that can co-optimize transmission and generation expansion and operations. However, the total capacity of lines required for this purpose is no doubt dwarfed by the 100s of thousands of GW-miles of capacity estimated in this study as necessary to connect more than 3 TW of new wind and solar capacity by 2050 in the E+ scenario. The bulk of lines will be required simply to transfer power from where it is produced to where it is consumed, with geographic aggregation an important but second-order derive of long distance transmission expansion in future power systems.
2. All cases lack a transmission loss factor in transmission line capacity builds (aside from EER to EER region corridors which come with an EER applied loss factor of 5%)
3. We are using an MSA's share of regional population in 2020 to allocate their demand for new renewable electricity in the region. Changes in relative population sizes of MSAs by 2050 could affect this allocation (e.g. if one MSA grows more rapidly than another).
4. In the inter-regional transmission balancing step, we do not explicitly re-balance if more capacity crosses regional borders than is specified by EER RIO model outputs for inter-regional transmission capacities. MSA-to-MSA balancing may implicitly include some re-balancing, but it does not address it explicitly. (It is assumed that although transmission has been built to transfer capacity to a specific MSA, that capacity could meet loads anywhere along the transfer corridor before reaching the MSA.) Also note that we do not subtract off excess 2050 capacity if corridor already overbuilt for EER needs in 2020.
5. Renewable resource siting that does not consider supply needs of all MSAs within an EER region may lead to renewable capacity imbalances within (and across regions as noted in prior item) regions that then need to be addressed by additional MSA-to-MSA lines
    a. Use of smaller MSAs (~250,000 people) for renewable resource aggregation would help address this issue, but would increase time and challenge of balancing renewable resources between MSAs
6. All/most capacity missing from final transmission siting (e.g ~147 of 75637 sites in RE+ base, or < .02% of total capacity) is due to overlapping selected sites, which result in a spur line only being built to one of the sites. In some cases, the sites completely overlap as in Figure 9.
    a. (limitation/further work) to overcome site overlap problems we use site centers rather than edges, which could potentially add up to ~8km extra per site (sites are capped at 16 km2, max would occur in the case of long thin site) – perhaps balancing lack of a loss factor
7. In this iteration, we removed individual substation-to-MSA lines that carry capacities less than 500 MW and line distances greater than 300 miles (483 km). However, most (if not all) of these

substation-to-MSA lines run a much shorter distance before entering a corridor that is already populated with another substation-to-MSA line. This leads to the removal of a number of low-capacity projects from transmission processing on the grounds that they would not be viable **alone** due to the length of the substation-to-MSA run required. Yet, in a perfect forward planning world, these smaller projects would likely be made viable by a larger capacity substation-to-MSA line already running in a corridor they plan to connect into on their path to the nearest MSA. A future iteration of this process would likely divide all substation-to-MSA (and MSA-to-MSA corridors into sections using substations of a given capacity (E.g. >161 kV) along the corridor route, rather than just using endpoints as is done now. This would then allow the transmission build to become more granular and better reflect transmission upgrades along each section of a corridor. It would also likely lead to the inclusion of the smaller projects currently being excluded due to lower capacities and longer line distances. The start date of low-capacity projects would then lag 5 years behind the implementation date of a nearby larger capacity transmission line that would make them viable.

8. Improve spur and long-distance transmission cost surfaces with input from NREL, along with transmission corridors able to be accessed by different classes of TX.
    a. As part of process, upgrade to latest transmission and substation maps and include proposed transmission routes if possible (old Ventyx dataset scooped up by ABB and unavailable)
    b. Remove or better systematize substations added for visual presentation reasons (offshore and 6 onshore)
9. Use open source software for mapping to ease reproducibility by community. The selection of the ArcGIS Pro was expedient rather than systematic as Princeton has a University-wide license and the NZAP team was already using ESRI tools to site renewable resources.

7 References

[1] Department of Transportation, "Core Based Statistical Areas (National)," *Data.gov*, Feb. 03, 2020. https://catalog.data.gov/dataset/core-based-statistical-areas-national (accessed Jun. 08, 2020).

[2] National Renewable Energy Laboratory, "Renewable Electricity Futures Study," National Renewable Energy Laboratory, Golden,CO, NREL/TP-6A20-52409, 2012. Accessed: Jan. 21, 2019. [Online]. Available: https://www.nrel.gov/docs/fy12osti/52409-1.pdf

[3] Environmental Systems Research Institute (ESRI), *ArcGIS Pro*. 2020. [Online]. Available: https://arcgis.pro/

[4] R Core Team, "R: A language and environment for statistical computing. R Foundation for Statistical Computing," 2016, [Online]. Available: https://www.R-project.org

[5] EIA, "Form EIA-860 detailed data with previous form data (EIA-860A/860B)," *US Energy Information Administration*, Sep. 03, 2019. https://www.eia.gov/electricity/data/eia860/ (accessed Mar. 05, 2019).

[6] EIA, "Preliminary Monthly Electric Generator Inventory (based on Form EIA-860M as a supplement to Form EIA-860)," *Electricity*, Apr. 24, 2020. https://www.eia.gov/electricity/data/eia860m/ (accessed May 08, 2020).

[7] HIFLD, "Electric Substations," *Homeland Infrastructure Foundation-Level Data (HIFLD)*, Oct. 07, 2019. https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-substations (accessed Jun. 08, 2020).

[8] S. M. Cohen *et al.*, "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2018," National Renewable Energy Lab. (NREL), Golden, CO (United States), United States, Apr. 2019. doi: 10.2172/1505935.

[9] NREL (National Renewable Energy Laboratory), “2019 Annual Technology Baseline,” Golden, CO: National Renewable Energy Laboratory, 2019. Accessed: Jun. 10, 2020. [Online]. Available: https://atb.nrel.gov/
[10] HIFLD, “Electric Power Transmission Lines,” *Homeland Infrastructure Foundation-Level Data (HIFLD)*, Sep. 25, 2019. https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines (accessed Nov. 18, 2019).
[11] G. Maclaurin, N. Grue, A. Lopez, and D. Heimiller, “The Renewable Energy Potential (reV) Model: A Geospatial Platform for Technical Potential and Supply Curve Modeling,” National Renewable Energy Laboratory, Golden, CO, Technical Report NREL/TP-6A20-73067, Sep. 2019. Accessed: Mar. 04, 2020. [Online]. Available: https://www.nrel.gov/docs/fy19osti/73067.pdf
[12] JuliaLang.org, “The Julia Programming Language.” https://julialang.org/ (accessed Jun. 01, 2021).
[13] Grady, “AMERICAN ELECTRIC POWER Transmission Facts.” 2011. Accessed: Jul. 30, 2020. [Online]. Available: https://web.ecs.baylor.edu/faculty/grady/_13_EE392J_2_Spring11_AEP_Transmission_Facts.pdf
[14] R. Gutman, P. P. Marchenko, and R. D. Dunlop, “Analytical Development of Loadability Characteristics for EHV and UHV Transmission Lines,” *IEEE Trans. Power Appar. Syst.*, vol. PAS-98, no. 2, pp. 606–617, Mar. 1979, doi: 10.1109/TPAS.1979.319410.
[15] Wikipedia, “Pacific DC Intertie,” *Wikipedia*. Feb. 14, 2020. Accessed: Aug. 01, 2020. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Pacific_DC_Intertie&oldid=940711324
[16] Wikepedia, “Plains & Eastern Clean Line,” *Wikipedia*. Mar. 29, 2020. Accessed: Aug. 01, 2020. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Plains_%26_Eastern_Clean_Line&oldid=948032716
[17] Wikipedia, “Path 27,” *Wikipedia*. Aug. 20, 2020. Accessed: Sep. 16, 2020. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Path_27&oldid=973945387

8 Additional Tables and Figures

Table 10 Detailed steps undertaken in the first iteration of integrated resource to metropolitan service area (MSA) mapping and costing

Step	**Description**
1. Clean renewable resource site data (solar PV, onshore wind, offshore wind)	1. (ArcGIS Pro) *Selected solar PV/wind sites*: Use the tool, “Select by Attributes” in order to remove existing sites and sites missing a sited capacity from the analysis (or alternatively use the “Definition Query” tool).
2. Clean and limit existing infrastructure data according to NZAP first iteration parameters (transmission lines, substations, MSAs)	1. (ArcGIS Pro) *Substations*: Use the tool, “Select by Attributes” in order to remove substations which have no voltage rating or a voltage rating of less than 161 kV. 2. (ArcGIS Pro) *Substations*: Retain only one substation within each circular area (radius 500m) on the analysis map by a. Running “Near” function on substations using a radius of 500m b. For all substations that are closer than 500m, use “Buffer” to increase their radius by 500m c. For all buffered substations, use “Dissolve” to merge overlapping substations into a single item d. Use “Feature to point” to return dissolved substation polygons into points again

	e. Use “Merge” to add substation points from the prior step with all substations from step 2a that were not within 500 meters of another substation. 3. (ArcGIS Pro) *MSAs*: Use the tool, “Select by Attributes” in order to remove MSAs with a 2020 population of less than 750,000 from the analysis. 4. (ArcGIS Pro) *Substations*: Use “Copy”, “Paste” and “Move” tools to duplicate any substation and move it to the center of any MSA that lacks a substation of 161 kV or greater within its boundaries. 5. (ArcGIS Pro) *Substations*: Use “Copy”, “Paste” and “Move” tools to duplicate any substation and move it offshore wind areas having more than one offshore wind site. 6. (ArcGIS Pro) *Substations*: Use “Copy”, “Paste” and “Move” tools to duplicate any substation and move it offshore wind areas having more than one offshore wind site. 7. (ArcGIS Pro) *Substations*: Use “Copy”, “Paste” and “Move” tools to duplicate any substation and move it selected locations in order to improve visual presentation in some areas of nation.
3. Create a differential cost surface to use in selecting the least cost pathway between each renewable resource and a substation (spur line)	1. (ArcGIS Pro) Use feature and raster tools to combine EER regional boundaries, existing transmission lines, and NREL [8], [9] costs into a single raster image with an embedded differential cost structure appropriate for the siting and costing of spur lines.
4. Create a differential cost surface to use in selecting the least cost pathway between a substation connected to a spur line and MSA substations (transmission lines) [16]	1. (ArcGIS Pro) Use feature and raster tools to combine EER regional boundaries, existing transmission lines, and NREL [8] costs into a single raster image with an embedded differential cost structure appropriate for the siting and costing of long-distance transmission lines.
5. Draw the least cost spur line connecting a renewable resource to a substation	1. (ArcGIS Pro) *Spur line start point*: Use the tool “Feature to point” on *solar PV/wind sites* in order create a spur line start point at the center of each sited resource. 2. (ArcGIS Pro) *Spur line end points:* Use the “Cost Distance” tool on the *substations* data set in order to create the distance and direction inputs required for least cost mapping between spur line start and potential end points. 3. (ArcGIS Pro) *Spur lines*: Use the “Cost Path as Polyline” tool to find the least cost path from every spur line start point to any spur line end point, while maintaining the unique identifier for each spur line start point in the attributes of the drawn spur line. 4. (ArcGIS Pro) *Spur lines*: Use “Spatial Join” to combine *spur lines* attributes with the unique identifier of the “closest” substation to the spur line.
6. Draw the least cost transmission line connecting each substation identified in the prior step to a substation in an MSA (transmission line)	1. (ArcGIS Pro) *transmission line start point A*: Use “Add Join” tool without the “Keep all Target Features” setting, in order to momentarily combine *substation*s layer with the unique substation identifier attached to each spur line. a. Use “Feature to Feature” tool to export the reduced substation layer to its own transmission starting point layer b. Remove all “joins” from substation layer

[16] This nomenclature is introduced in this Annex in order to ease referral to these types of lines and differentiate them from both spur lines and long-distance transmission lines built in following sections to accomplish other goals.

	2. (ArcGIS Pro) *transmission line start point B*: Use “Spatial Join” tool to select and create a layer with only substations that overlap with the selected sites layer. a. Then use “Select by Location” tool (with the *transmission line start point B layer* as the input feature and *transmission start point A* layer as the selecting feature) to select only *transmission line start point B items* that do not overlap with the *transmission start point A* layer. b. Use “Merge” to add non-overlapping *transmission line start point B items to the transmission start point A layer* 3. (ArcGIS Pro) *transmission line end points:* Use the “Select by Location” tool on the *substations* data set (with the *MSA* layer as an input) to select only substations within MSA boundaries. a. Use “Feature to Feature” tool to export the MSA-only substation layer to its own *transmission line end points* layer 4. (ArcGIS Pro) *transmission line end points:* Use the “Cost Distance” tool on the *transmission line end points* data set in order to create the distance and direction inputs required for least cost mapping between transmission line start and potential end points. 5. (ArcGIS Pro) *transmission lines*: Use the “Cost Path as Polyline” tool to find the least cost path from every transmission line start point to any transmission line end point. 6. (ArcGIS Pro) *transmission lines*: Use “Spatial Join” to combine *transmission line* attributes with the unique identifier of the “closest” substation to the spur line (along with aspects of the nearest final destination Metro region)
7. Clean spur and transmission lines, and estimate the capacity weighted cost and MW-km of spur and transmission lines	1. (ArcGIS Pro) Use “Copy Rows” or “Table to Excel” to export all input data sets needed by the R scripts used in the next steps 2. (R) *Spur line costs*: Estimate the cost of each spur line by multiplying the capacity of each *Selected solar PV/wind sites (MW)* by the associated *Spur line* cost (USD2018/MW) determined by “Cost Path as Polyline”. 3. (R) *Spur line costs*: Refine the estimated cost of each spur line by adding in the result of multiplying the capacity of each *Selected solar PV/wind sites (MW)* by the uniform transmission tie in cost (USD2018/MW) given in Table 3. 4. (R) *transmission line capacity*: Estimate the capacity of each *transmission line* by aggregating the maximum capacity arriving on the *spur lines* connected to the *transmission line*. 5. (R) *transmission line costs*: Estimate the cost of each transmission line by multiplying *transmission line capacity* by the transmission line cost (USD2018/MW) determined by “Cost Path as Polyline”. 6. (R) *Spur line MW-km*: Estimate the MW-km of each spur line by multiplying the capacity of each *Selected solar PV/wind sites (MW)* by the associated *Spur line* km determined by “Cost Path as Polyline”. 7. (R) *transmission line MW-km*: Estimate the MW-km of each transmission line by multiplying the capacity aggregated at the starting point of each transmission line by the transmission line km determined by “Cost Path as Polyline”.

	8. (R) *transmission line costs:* Remove the costs connected to any transmission line with a transmission line capacity of less than 500 MW and a length of greater than 483 km (300 miles). 9. (R) *transmission line MW-km:* Remove the MW-km connected to any transmission line with a transmission line capacity of less than 500 MW and a length of greater than 483 km (300 miles).

Table 11 A list of potential bad/problematic data flags that did not result in the removal of sited resources from the analysis, along with any steps taken to clean the data

Flag	**Action**	**E+ base**	**E+ constrained**	**RE+ base**	**RE- base**	**REF**
Site generation (egen) of 0 or NULL	Change NULL to 0 and ignore	14	5	10	14	14
Site missing EER region allocation	Manually add EER region	10	8	10	10	10
Site boundary overlaps another site (see Figure 9 for example)	Ignore overlap and use site center for mapping	4,180	3,321	2,487	709	504
Sites with the same center point	Ignore	179	692	115	115	115

Table 12 Detailed steps undertaken in integrated MSA-to-MSA mapping and costing

Step	**Description**
1. Determine the inter-regional MSA-to-MSA transmission corridor builds needed to meet the EER model specified inter-regional transmission capacity in 2050	1. (R) Determine EER inter-regional transmission capacity builds for each NZAP scenario in 2050 2. (R) Aggregate gross renewable capacity transfers across regions in 2050 via spur and transmission lines 3. (R) If NZAP gross cross border capacity transfer falls short of the EER corridor build, then specify the missing capacity for a build in the EER corridor
2. Determine the MSA-to-MSA transmission needed to ensure each MSA in the analysis has access to the renewable generation needed to cover its regionally allocated demand to be supplied by new renewables	1. (R) Aggregate renewable capacity arriving via spur and transmission lines to destination MSAs in NZAP determined time increments (e.g. 5 years) 2. (R) Determine the amount of oversupply (positive number) or shortfall (negative number) of renewable generation at each MSA in 2050 (see steps A through J in Section 1) 3. (R/Julia/Excel) If an MSA's aggregate renewable capacity arriving via spur and transmission lines in 2050 does not meet the MSA's total required 2050 renewable energy demand, then determine the optimal configuration needed to transfer renewable energy from MSA(s) having excess supply with the lowest total cost. In some cases where the closest MSAs also show a deficit or are short on capacity, multiple MSAs will need to be connected via transmission in order to deliver capacity to the MSA. This may also increase inter-regional transmission corridor capacities beyond the capacity previously specified if the MSAs involved are connected across EER region borders. 4. (R) For time-step builds, the source MSA supplying the bulk of renewable capacity to any other MSA will set the rate of construction of the transmission corridors connecting MSAs.

3. Draw the least cost pathway for each identified MSA-to-MSA transmission corridor	1. (ArcGIS Pro) *MSA center points:* Use the tool “Feature to point” on the *MSA* layer in order specify all potential MSA-to-MSA transmission start and end points at the center of each sited resource.
	2. (ArcGIS Pro) *MSA-to-MSA transmission corridor*: Iterate as needed in for each individual *MSA-to-MSA transmission* n corridor, or in groups.
	    a. Using the “Select” tool, manually select an *MSA center point* as the end point for any *MSA-to-MSA transmission* corridor
	    b. Use the “Feature to Feature” tool to export the *MSA-to-MSA transmission end point* to its own layer
	    c. Use the “Cost Distance” tool on the *MSA-to-MSA transmission end point* in order to create the distance and direction inputs required for least cost mapping of the MSA-to-MSA transmission corridor
	    d. Using the “Select” tool, manually select all *MSA center points* that require connection to the *MSA-to-MSA transmission end point*
	    e. Use the “Feature to Feature” tool to export the MSA center points to an *MSA-to-MSA transmission start point* layer
	    f. *MSA-to-MSA transmission corridor*: Use the “Cost Path as Polyline” tool to find the least cost path from the *MSA-to-MSA transmission start points* to the *MSA-to-MSA transmission end point*s
	    g. Use attribute table tools and/or “Transpose Fields” tool to manually add the 2050 and time increment capacities of each *MSA-to-MSA transmission* line drawn in prior steps

5. Clean MSA-to-MSA transmission corridors and estimate the capacity weighted cost and MW-km of each corridor	1. (ArcGIS Pro) Remove an MSA-to-MSA transmission corridor from the transmission analysis if the corridor is **both** longer than 483 kilometers (km) and is designed to transfer less than 500 MW of aggregated renewable capacity. 2. (ArcGIS Pro) Use “Copy Rows” or “Table to Excel” to export all input data sets needed by the R scripts used in the next steps 3. (R) MSA-to-MSA *transmission corridor* costs: Estimate the final or incremental cost of each *MSA-to-MSA transmission* corridor by multiplying the final or incremental capacity of each MSA-to-MSA transmission corridor by the associated *MSA-to-MSA transmission corridor* cost (USD2018/MW) determined by “Cost Path as Polyline”. 4. (R) *MSA-to-MSA transmission corridor* MW-km: Estimate the final or incremental MW-km of each MSA-to-MSA transmission corridor by multiplying the final or incremental capacity of each MSA-to-MSA transmission corridor by the *MSA-to-MSA transmission corridor* km determined by “Cost Path as Polyline”.

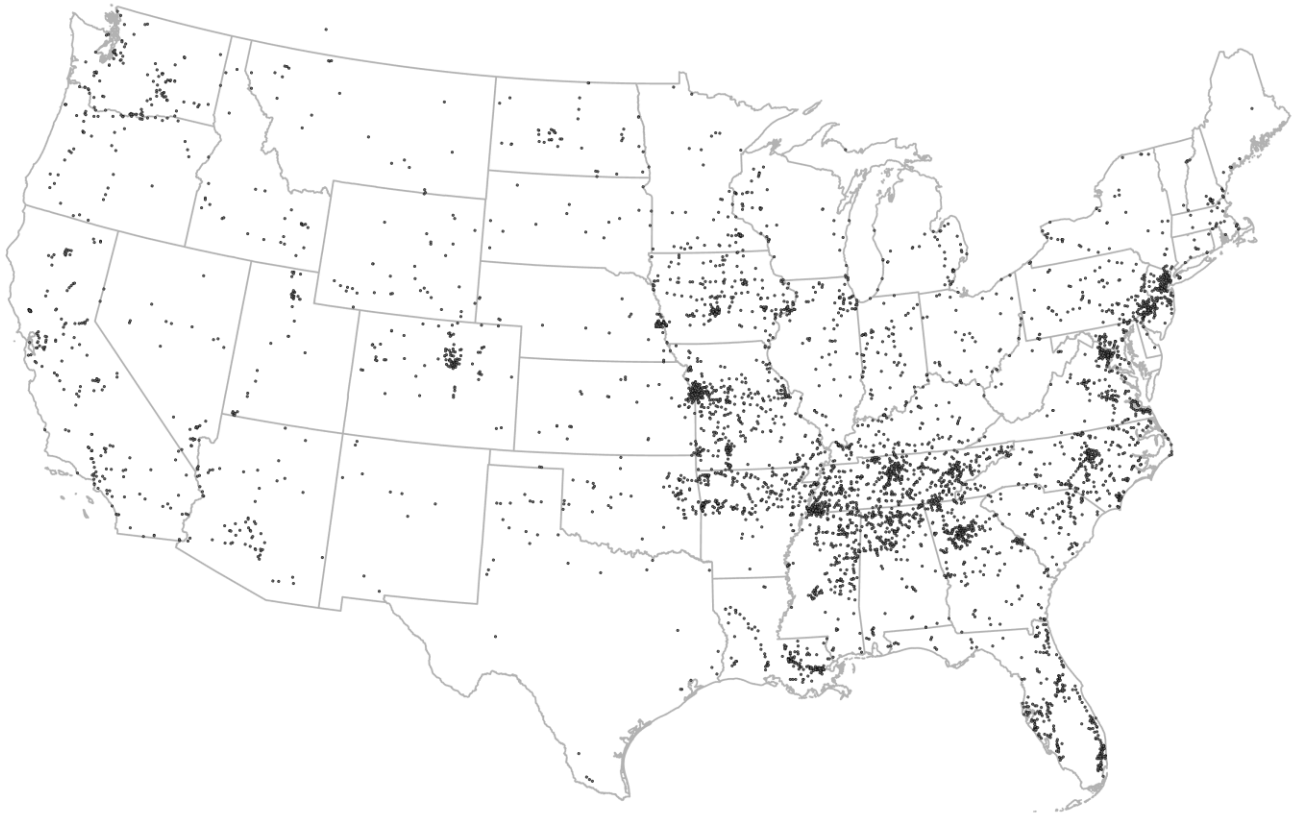


Figure 5 The 6,167 substations identified as having a rating greater than or equal (>=) to 161 kV in [7]

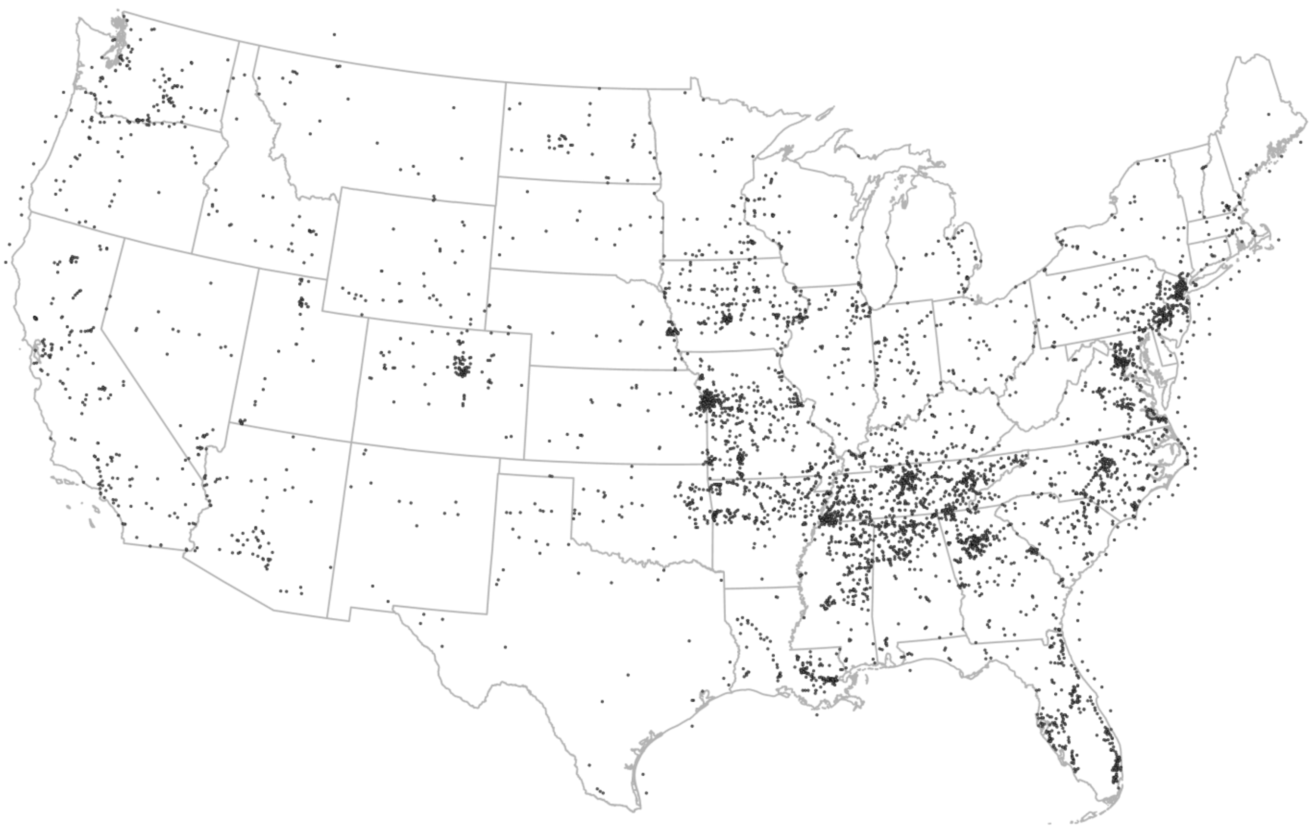


Figure 6 Substations >= 161 kV [7] along with the 60 "substations" (collection points) added in offshore areas, the 3 substations added at the center of MSA regions, and the 5 added to reduce spur line delta patterns onshore

Table 13 Spur line costs per MW-mile aggregated to EER model regions from [8], and aggregated to an average across offshore technology types from [9]

EER region	230V spur-line costs (USD2013/MW-mile unless otherwise marked)
desert southwest agg.	$ 3,901
california agg.	$ 5,200
texas agg.	$ 3,901
florida agg.	$ 4,101
upper midwest agg.	$ 4,101
new england agg.	$ 5,200
utah/nevada agg.	$ 3,901
pacific northwest agg.	$ 3,901
new york agg.	$ 5,200
mid-atlantic and great lakes agg.	$ 4,650
rocky mountains agg.	$ 3,901
lower midwest agg.	$ 3,800
louisiana and ozarks agg.	$ 4,409
southeast agg.	$ 4,700
Offshore fixed	$ 32,230 (USD2017/MW-mile)
Offshore floating	$ 44,466 (USD2017/MW-mile)

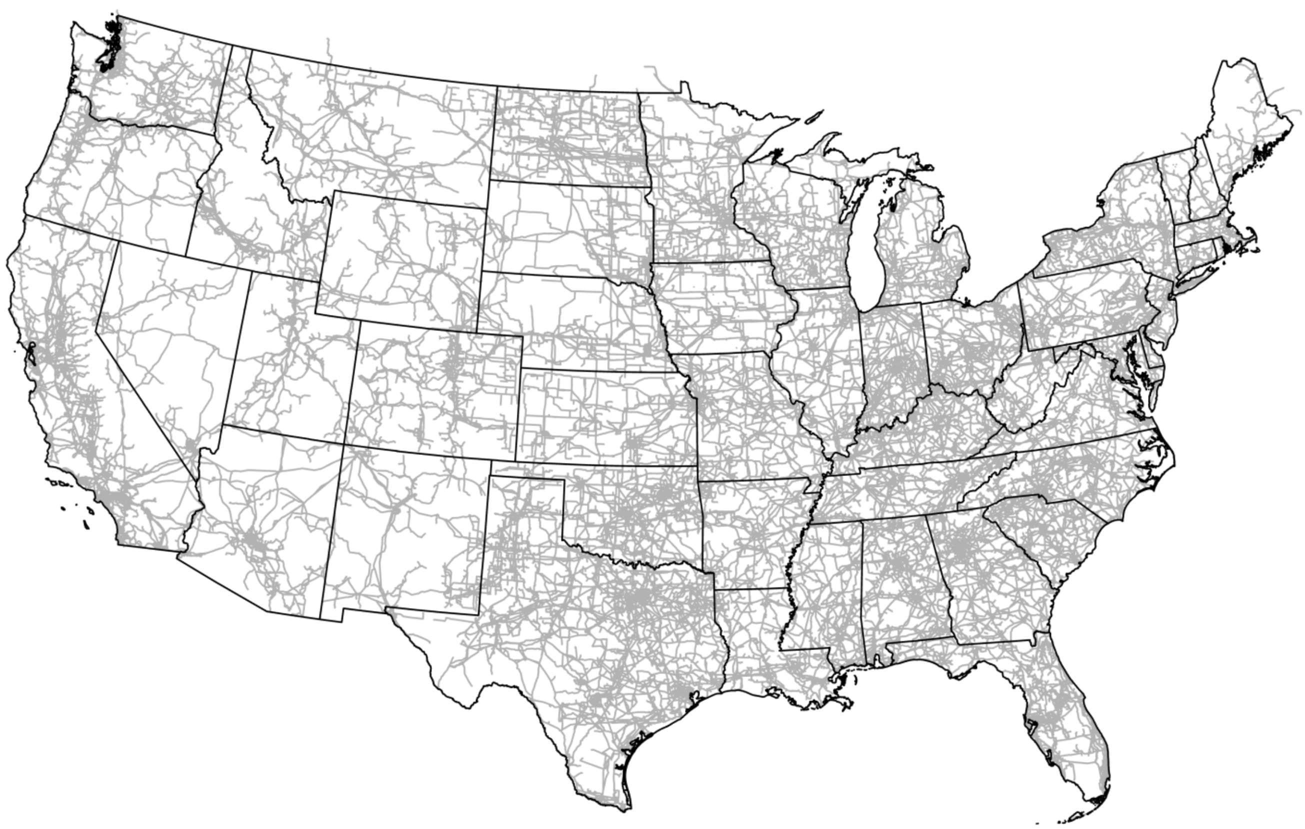


Figure 7 All 82,627 existing transmission corridors in [10]

Table 14 Long-distance transmission line costs per MW-mile aggregated to EER model regions from [8]

EER region	345, 500, 765 kV long distance transmission (USD2013/MW mile)
desert southwest agg.	$ 1,351
california agg.	$ 2,751
texas agg.	$ 1,351
florida agg.	$ 1,351
upper midwest agg.	$ 975
new england agg.	$ 3,500
utah/nevada agg.	$ 1,351
pacific northwest agg.	$ 1,351
new york agg.	$ 3,000
mid-atlantic and great lakes agg.	$ 1,175
rocky mountains agg.	$ 1,351
lower midwest agg.	$ 900
louisiana and ozarks agg.	$ 2,413
southeast agg.	$ 1,225

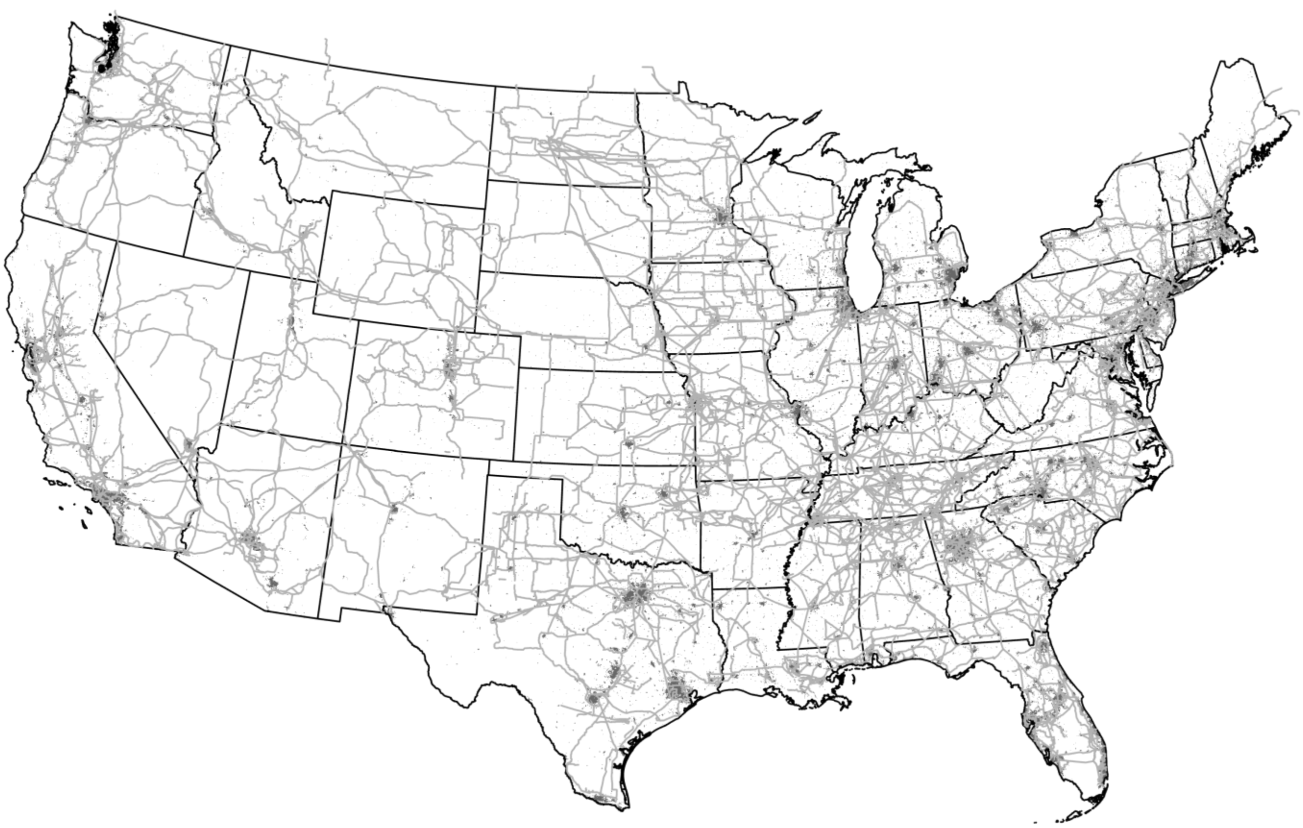


Figure 8 The 13,655 existing transmission corridors marked explicitly as having a voltage rating of greater than or equal to 161 kV in [10]

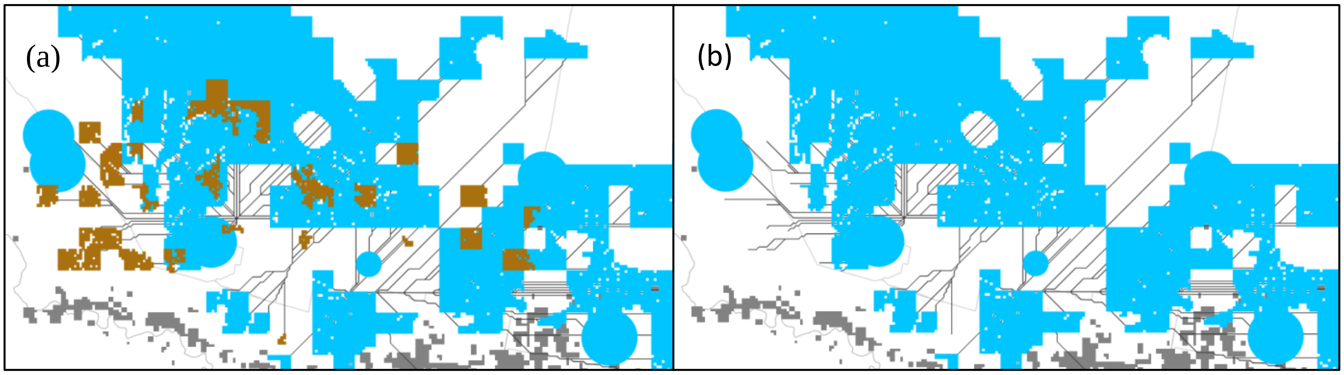


Figure 9 Example of site overlaps in some scenario/cases, (a) shows solar PV in orange and wind in blue, (b) shows just wind sites

Table 15 transmission corridor characteristics for E+ base scenario/case

Bin	Voltage type	Voltage class (circuits)	Transmission type	Corridors	Lines	Circuits	Line MW average	GW-km
2	HVAC	230 kV (1)	spur	40,627	40,627	40,627	75	95,439
2	HVAC	345 kV (1)	all non-spur	543	543	527	154	11,430
2	HVAC	345kV (2)	all non-spur	248	248	496	583	19,566
2	HVAC	500kV (1)	all non-spur	40	40	40	853	5,377
2	HVAC	765 kV (1)	all non-spur	631	1,242	1,242	1653	344,824
3	HVDC	500 kV (1)	all non-spur	43	95	95	2181	196,233
			Totals	**42,132**	**42,795**	**43,043**	**139**	**672,869**

9 Appendix (full set of transition maps)

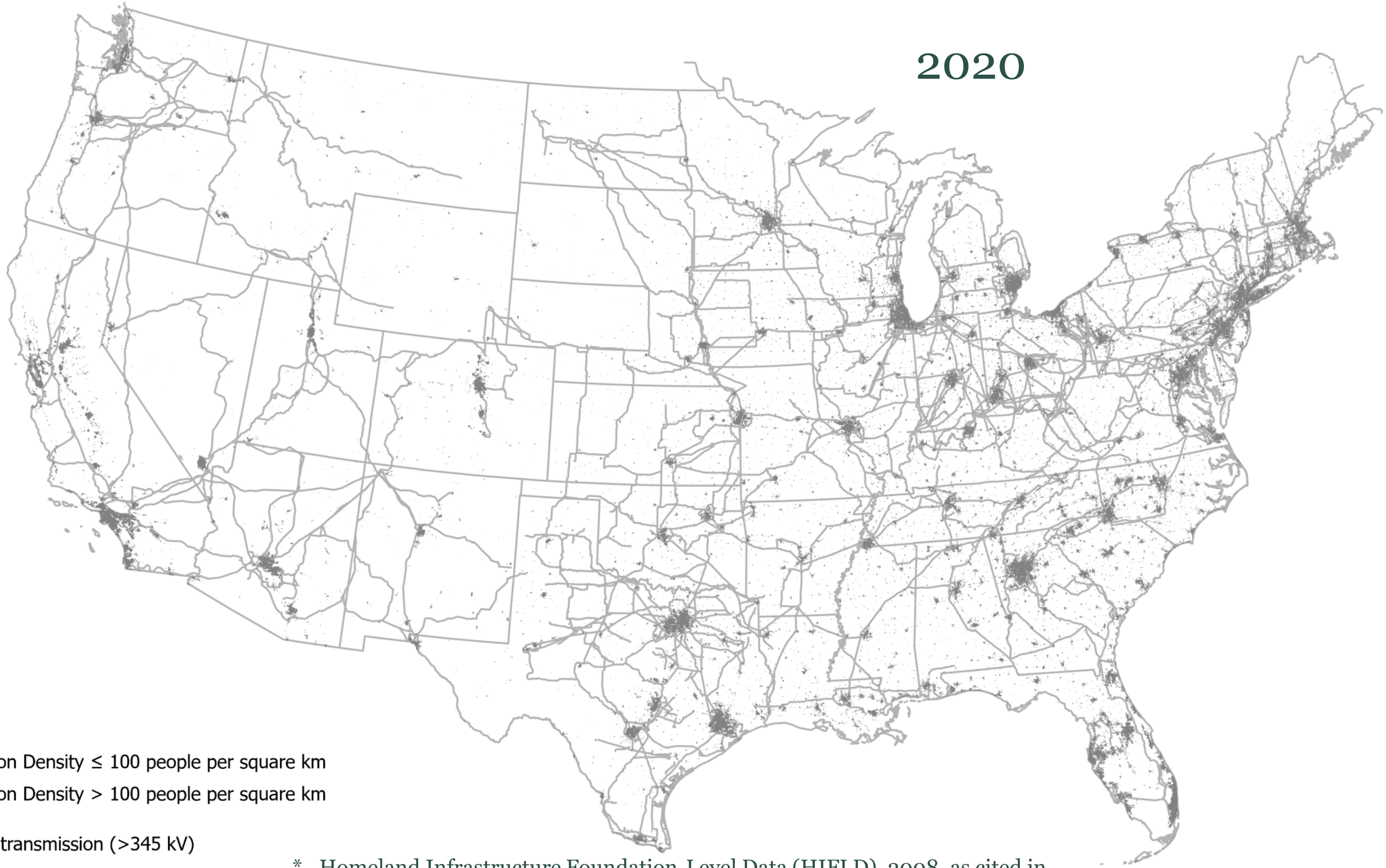
Appendix: Maps of high voltage transmission capacity additions supporting wind and solar generation

1 PRINCETON UNIVERSITY andlinger center for energy+the environment

High Meadows Environmental Institute Carbon Mitigation Initiative

Transmission system in 2020 (≥ 345 kV lines shown)

Total transmission capacity: ~320,000 GW-km*



Transmission Capacity (GW)

- 0.000512403
- 0.000512403 - 49.8853
- 49.8853
- 0.0005124
- 16.6288
- 33.257
- 49.8853

- Population Density ≤ 100 people per square km
- Population Density > 100 people per square km
- Existing transmission (>345 kV)

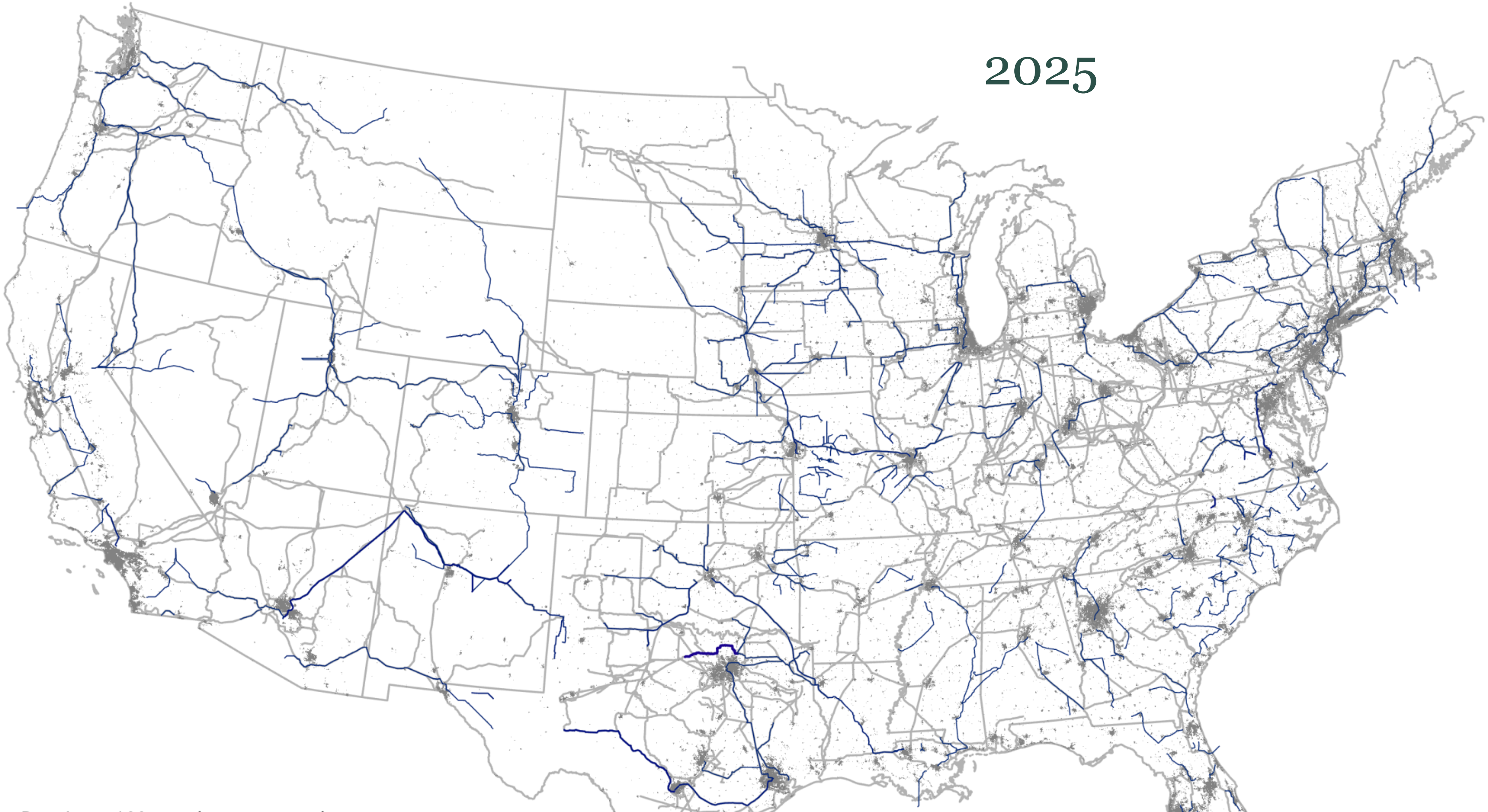
* Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.

Transmission expansions to support wind and solar generation in E+ scenario with Base siting availability, 2025

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 104,800 GW-km (33% increase from 2020)
- capital in service: 120 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)

0.000512403

0.000512403 - 49.8853

49.8853

0.0005124

16.6288

33.257

49.8853

Population Density ≤ 100 people per square km

Population Density > 100 people per square km

Existing transmission (>345 kV)

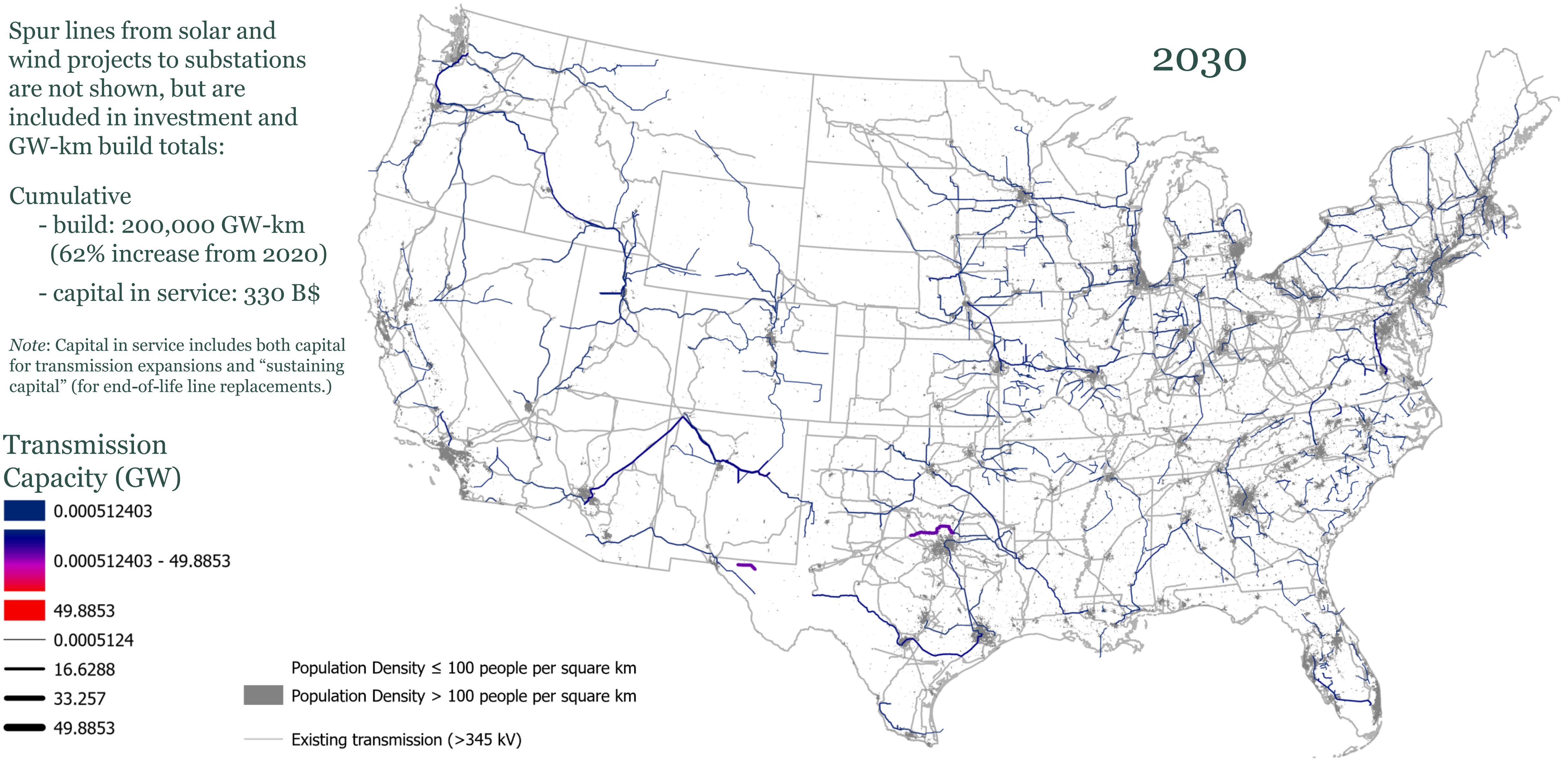
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in E+ scenario with Base siting availability, 2030

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 200,000 GW-km (62% increase from 2020)
- capital in service: 330 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



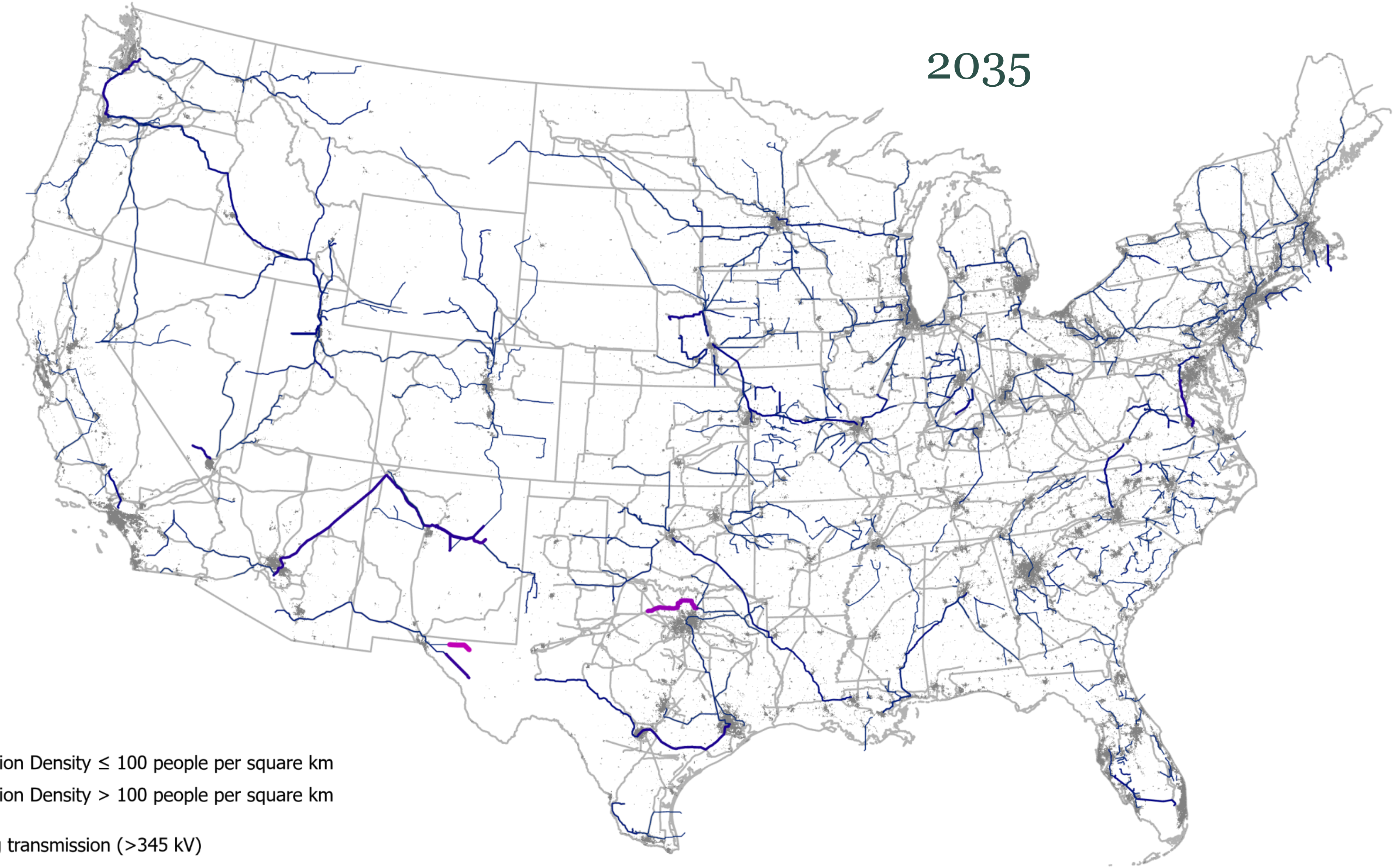
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in E+ scenario with Base siting availability, 2035

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 330,300 GW-km
  (103% increase from 2020)
- capital in service: 630 B$

Note: Capital in service includes both capital for transmission expansions and “sustaining capital” (for end-of-life line replacements.)



Transmission Capacity (GW)

- 0.000512403
- 0.000512403 - 49.8853
- 49.8853
- 0.0005124
- 16.6288
- 33.257
- 49.8853

Population Density ≤ 100 people per square km
Population Density > 100 people per square km
Existing transmission (>345 kV)

Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

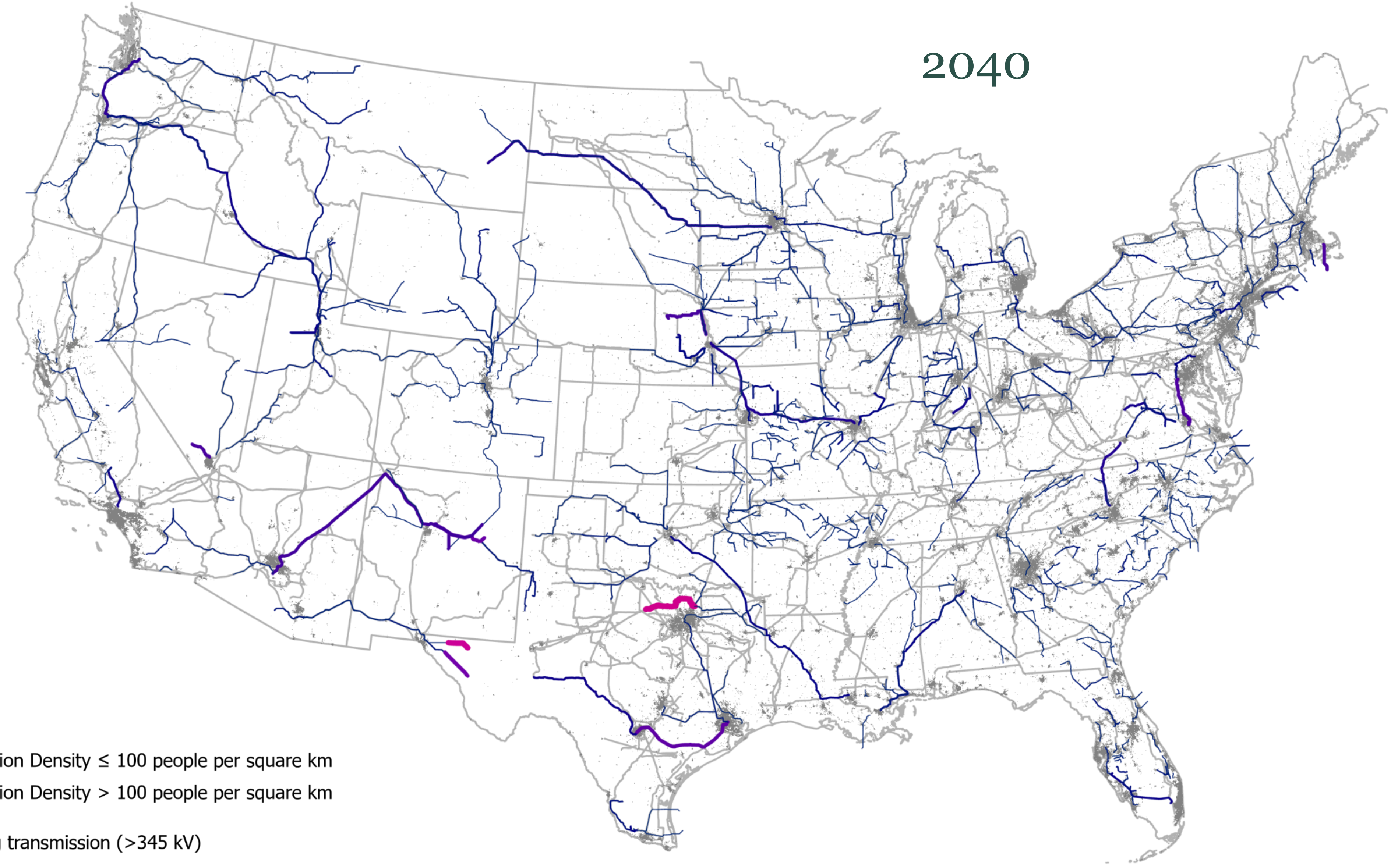
Transmission expansions to support wind and solar generation in E+ scenario with Base siting availability, 2040

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative

- build: 479,800 GW-km (150% increase from 2020)
- capital in service: 1,020 B$

Note: Capital in service includes both capital for transmission expansions and “sustaining capital” (for end-of-life line replacements.)



Transmission Capacity (GW)

0.000512403

0.000512403 - 49.8853

49.8853

0.0005124

16.6288

33.257

49.8853

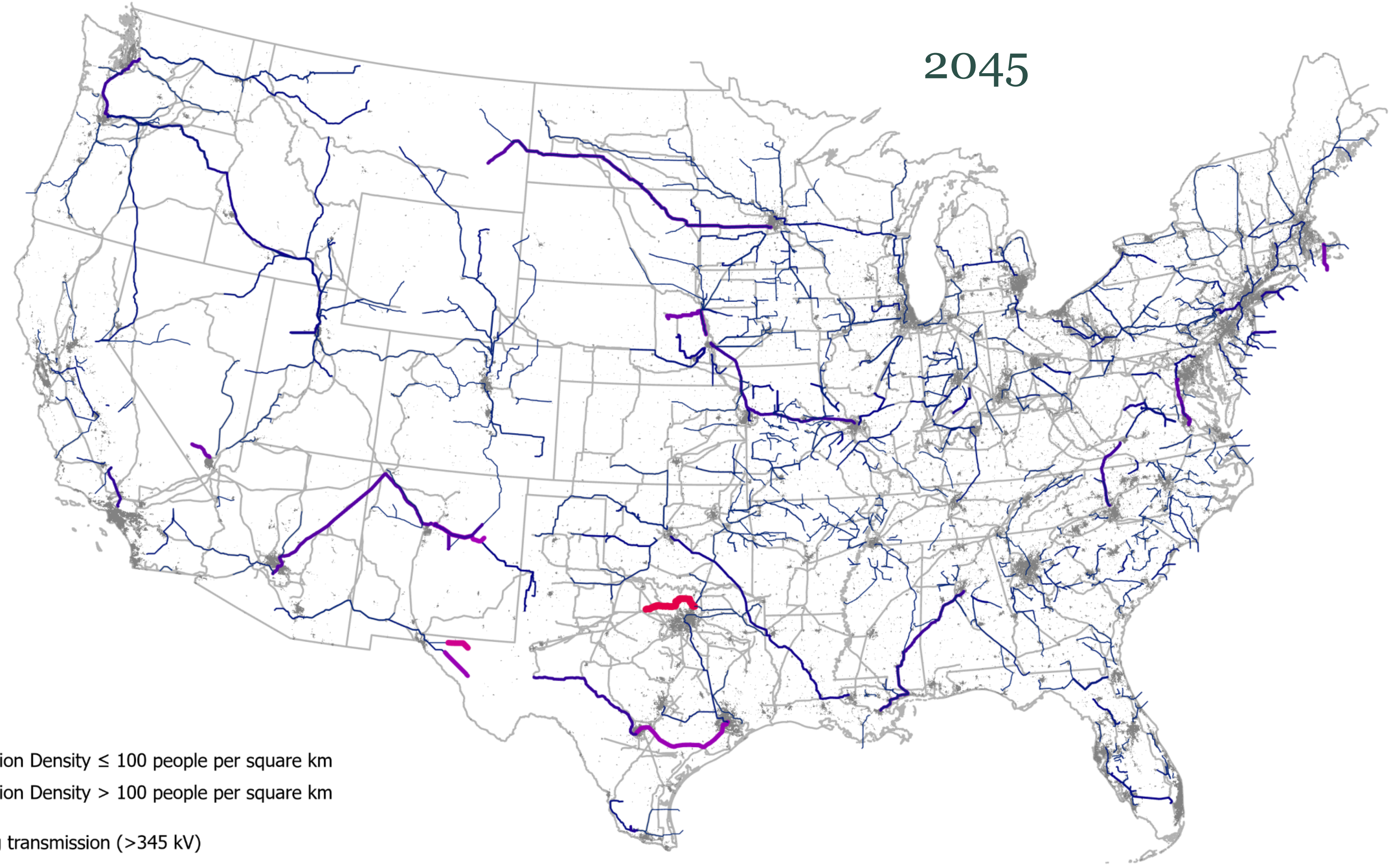
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in E+ scenario with Base siting availability, 2045

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 649,900 GW-km (203% increase from 2020)
- capital in service: 1,530 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

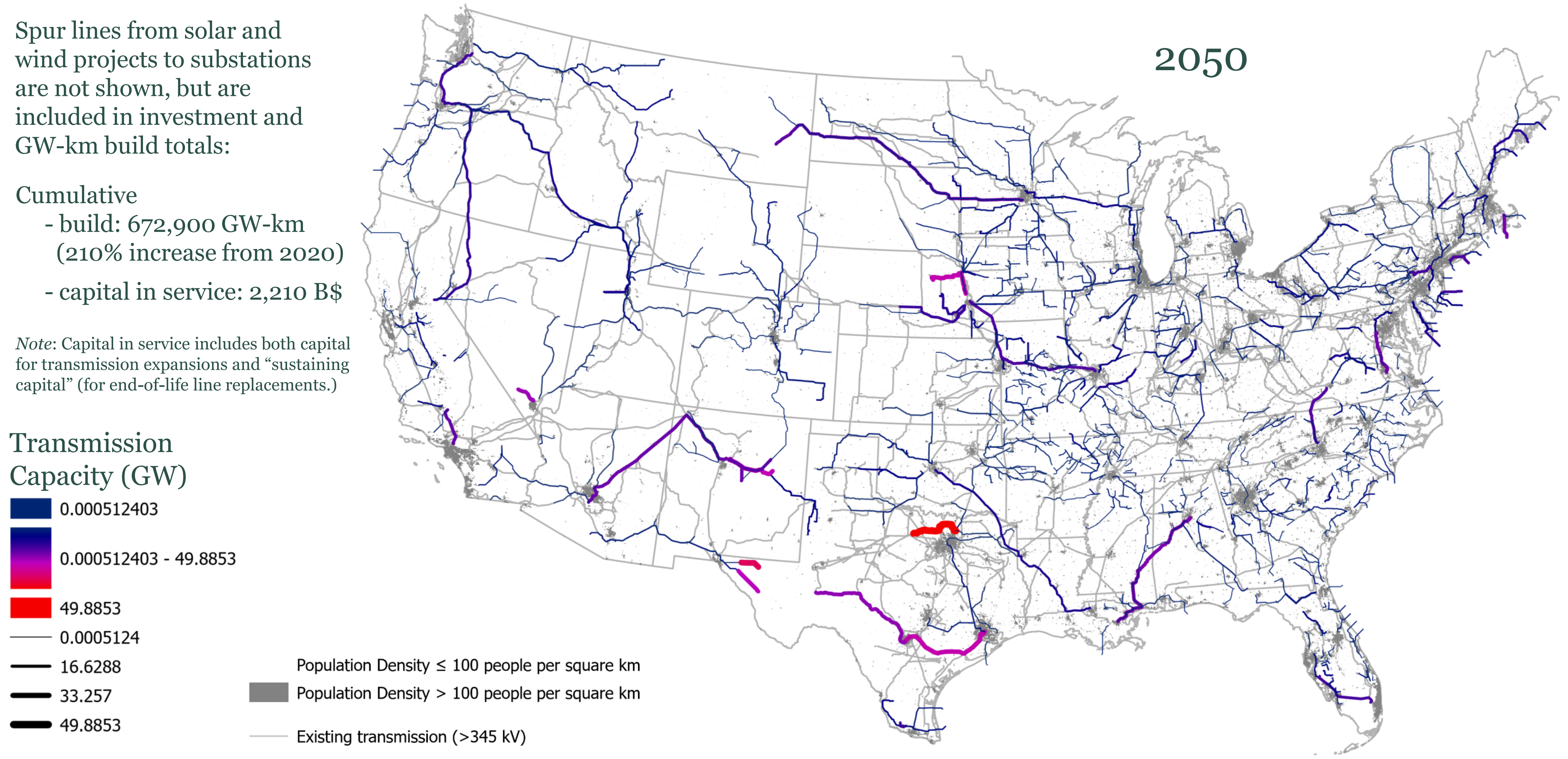
Transmission expansions to support wind and solar generation in E+ scenario with Base siting availability, 2050

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative

- build: 672,900 GW-km (210% increase from 2020)
- capital in service: 2,210 B$

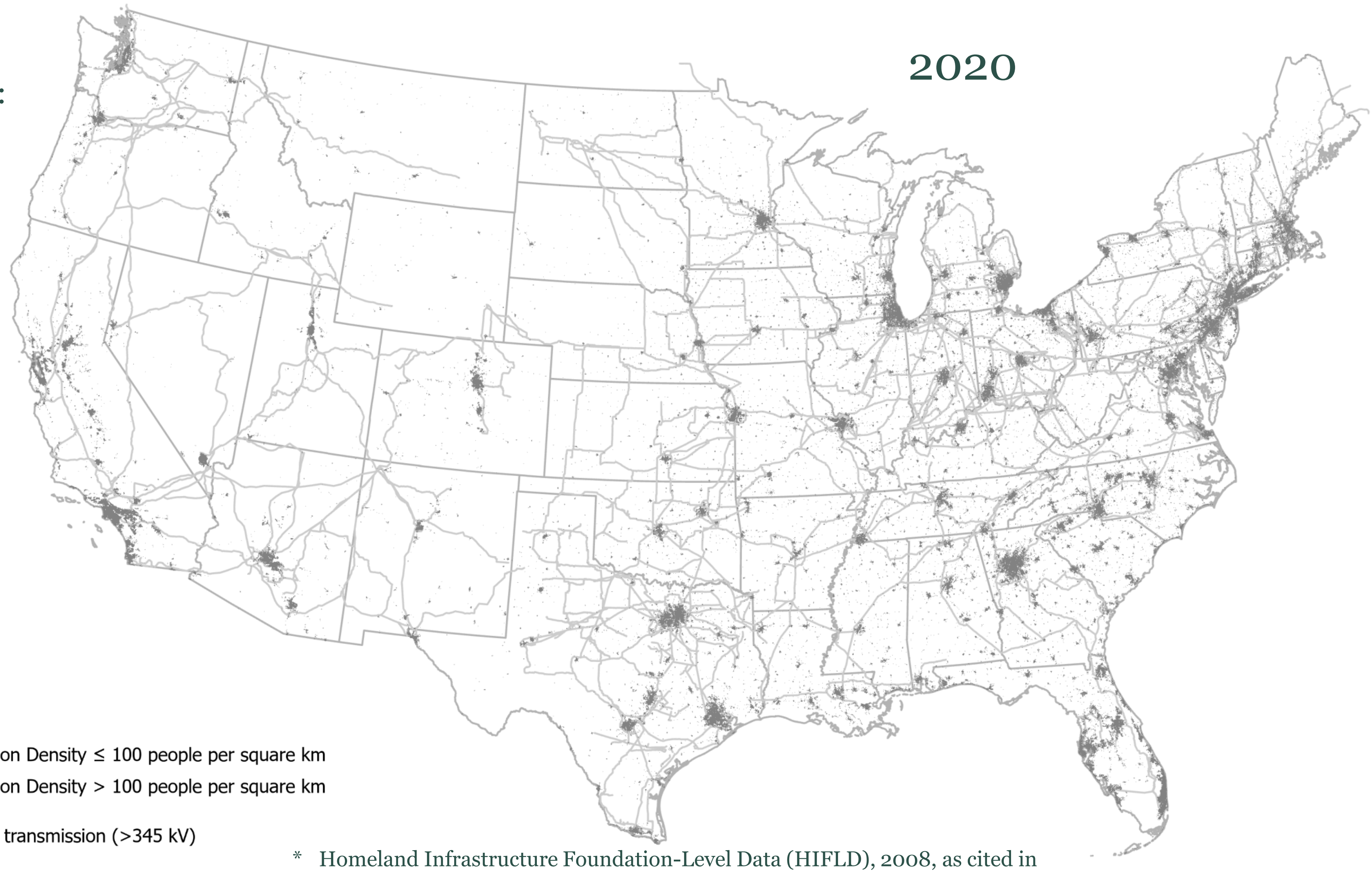
Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission system in 2020 (≥ 345 kV lines shown)

Total transmission capacity:
~320,000 GW-km*



* Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.

Transmission expansions to support wind and solar generation in E+ scenario with constrained siting availability, 2025

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 119,300 GW-km (37% increase from 2020)
- capital in service: 140 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)

Transmission Capacity (GW)

0.002

0.002 - 52.938

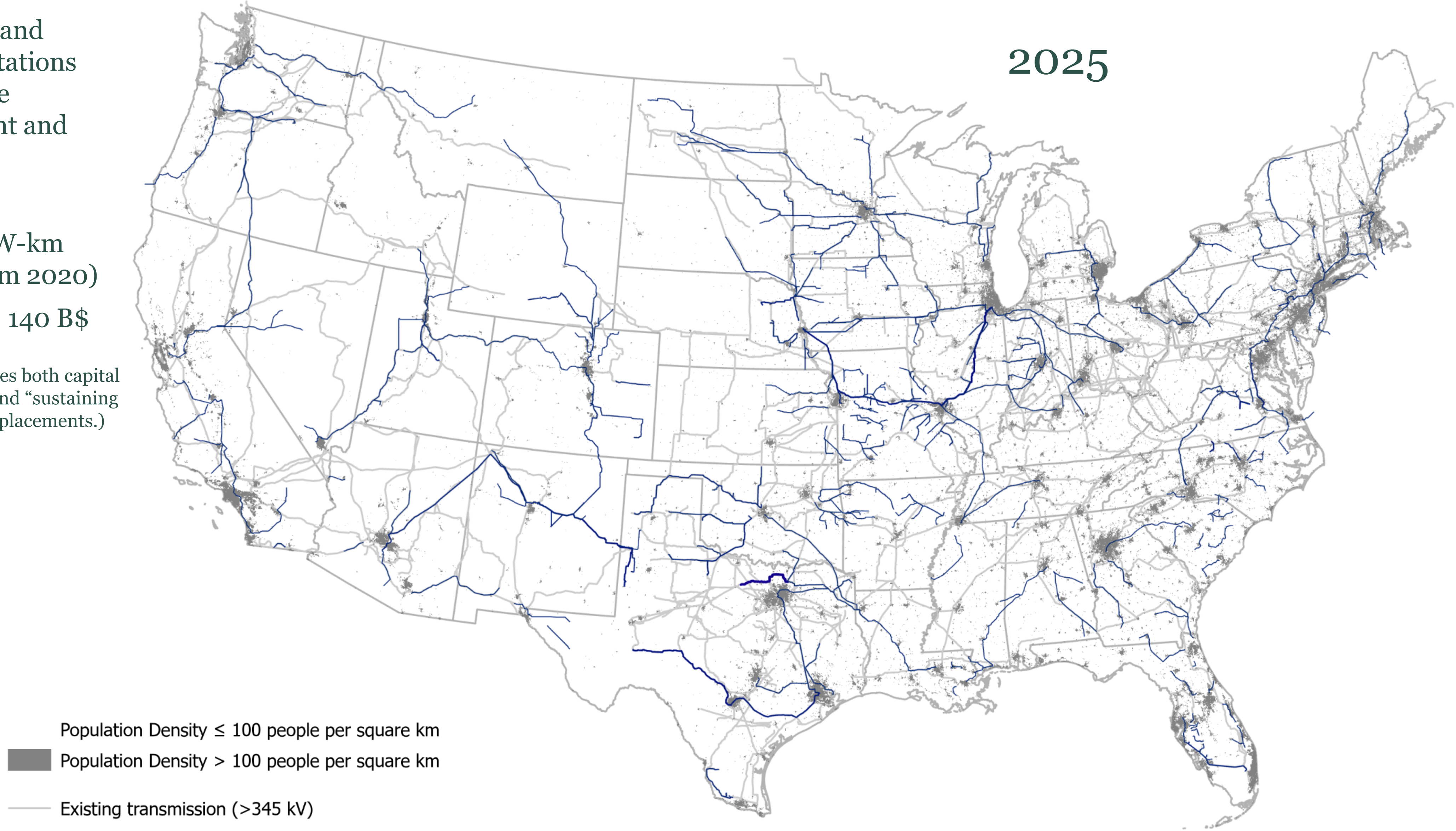
52.938

0.002

17.6473

35.2927

52.938



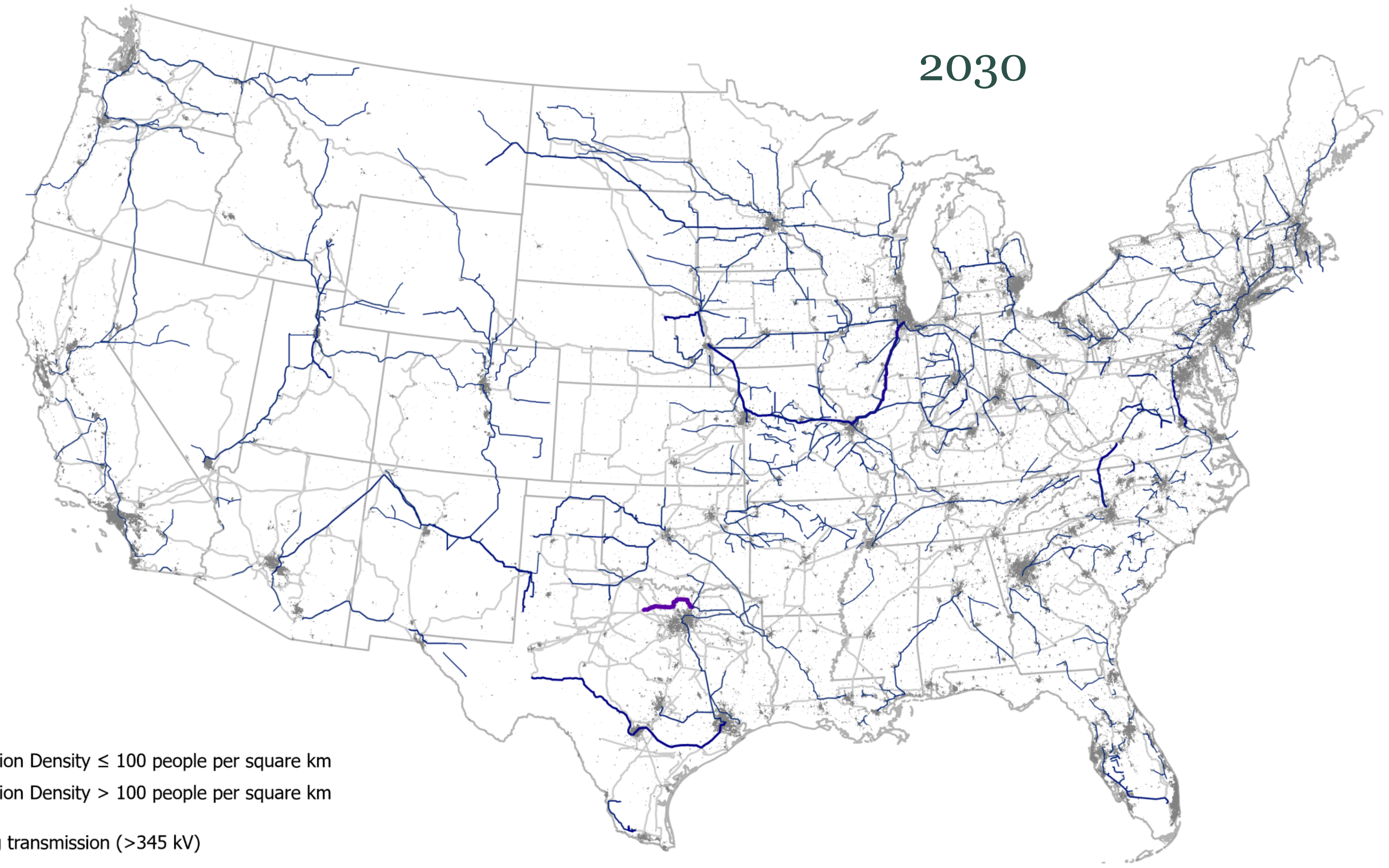
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in E+ scenario with constrained siting availability, 2030

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 234,200 GW-km (73% increase from 2020)
- capital in service: 385 B$

Note: Capital in service includes both capital for transmission expansions and “sustaining capital” (for end-of-life line replacements.)



Transmission Capacity (GW)
0.002
0.002 - 52.938
52.938
0.002
17.6473
35.2927
52.938

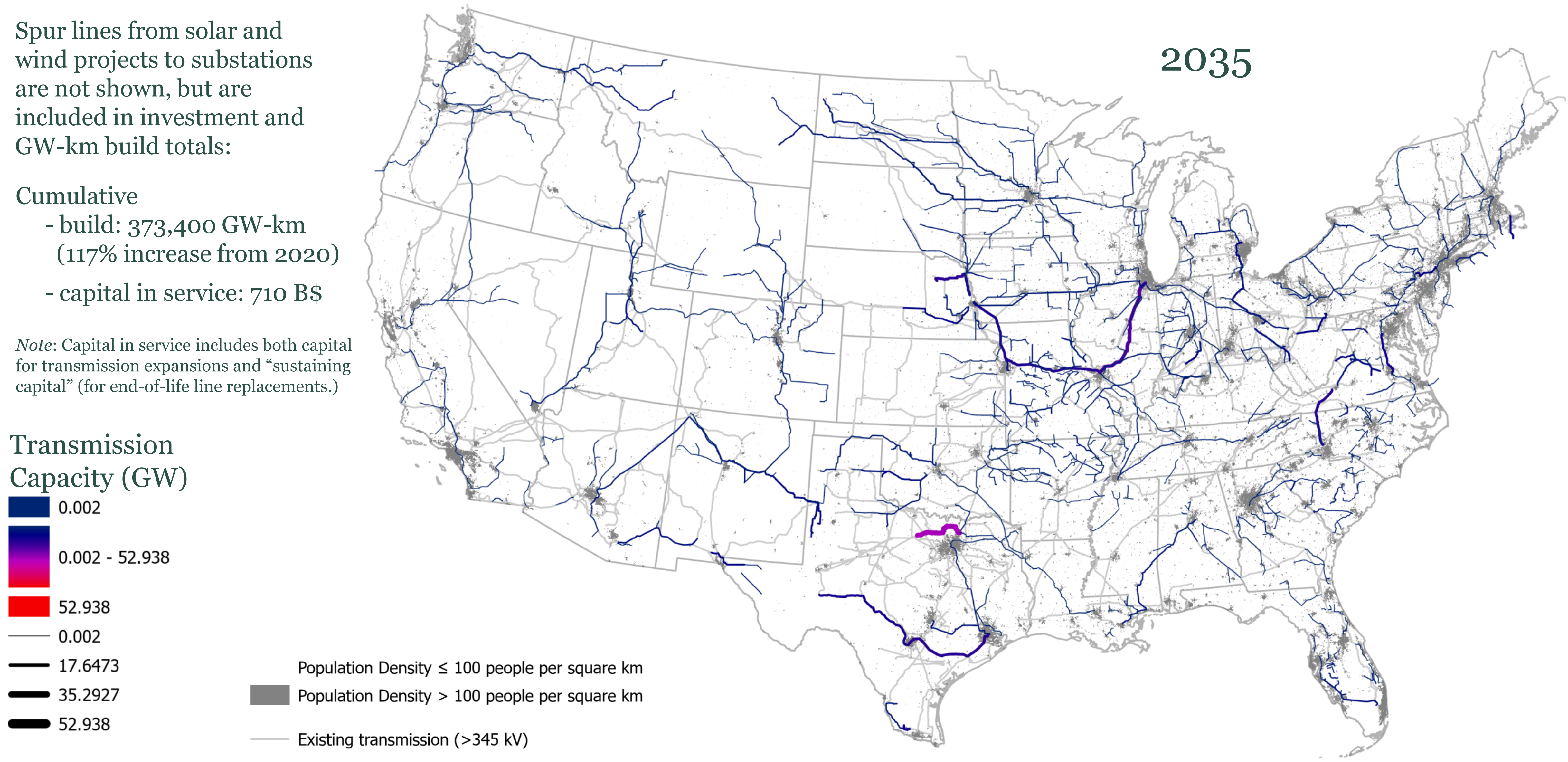
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in E+ scenario with constrained siting availability, 2035

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 373,400 GW-km (117% increase from 2020)
- capital in service: 710 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



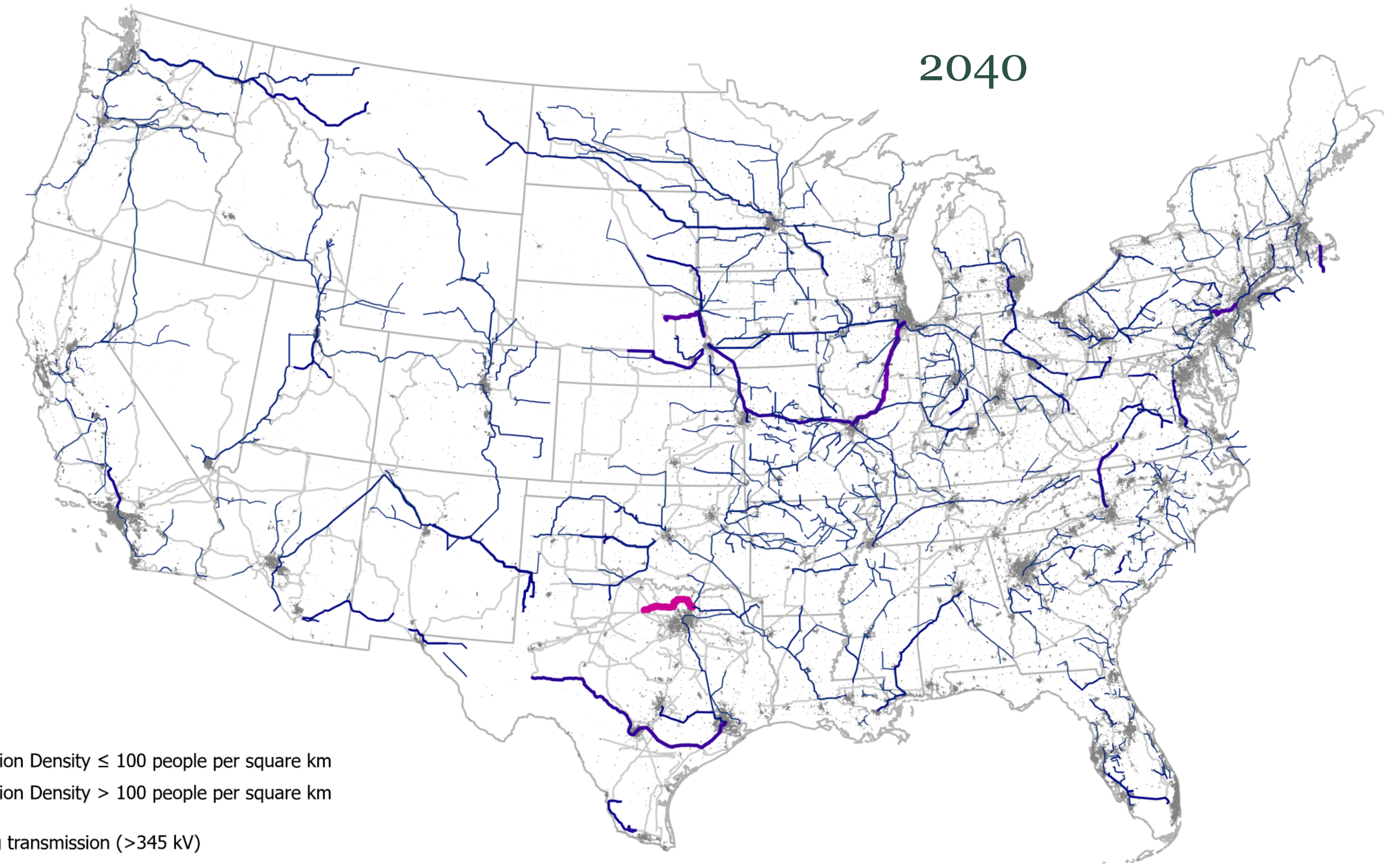
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in E+ scenario with constrained siting availability, 2040

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 523,500 GW-km
  (164% increase from 2020)
- capital in service: 1,110 B$

Note: Capital in service includes both capital for transmission expansions and “sustaining capital” (for end-of-life line replacements.)



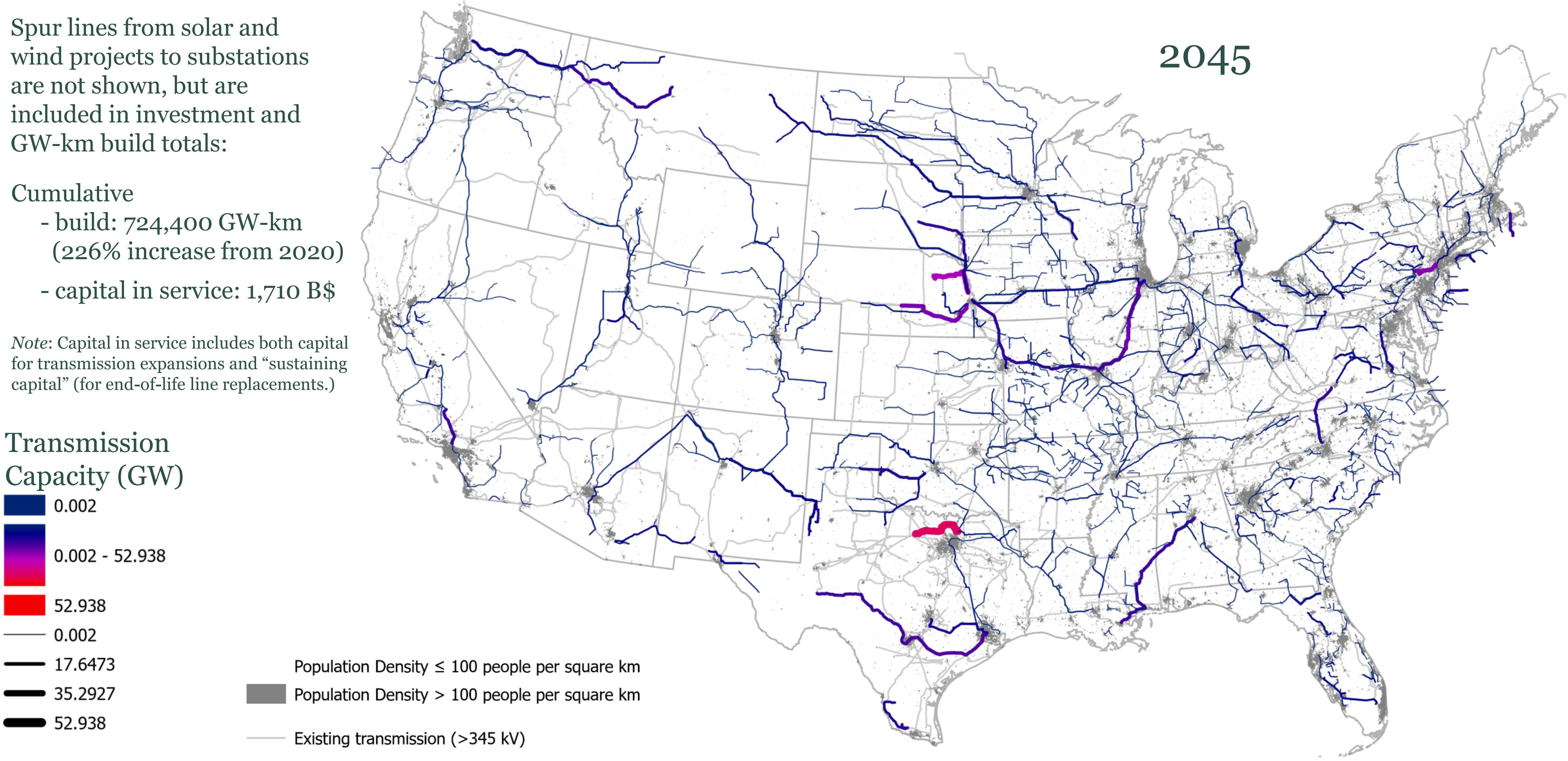
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in E+ scenario with constrained siting availability, 2045

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 724,400 GW-km (226% increase from 2020)
- capital in service: 1,710 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



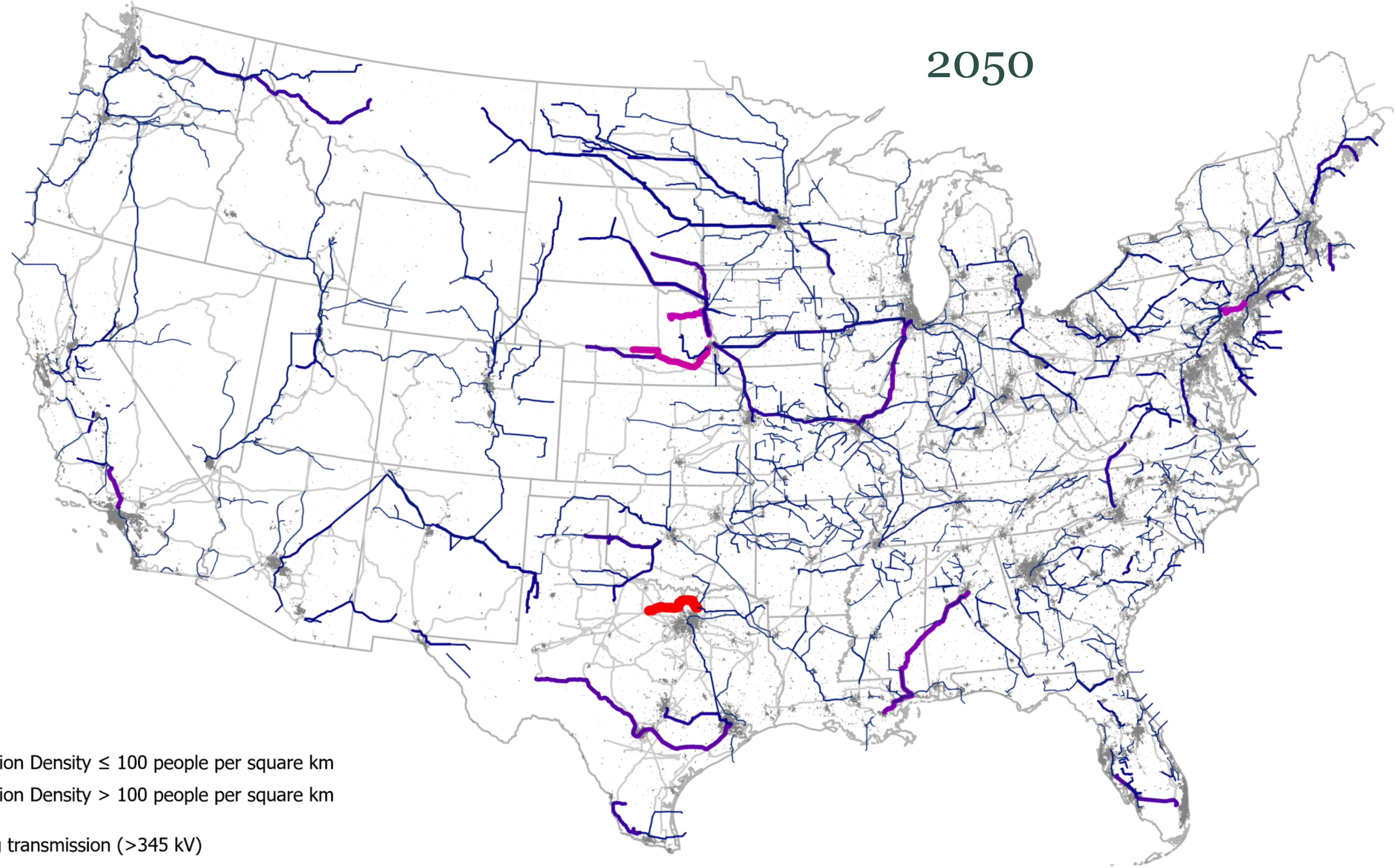
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in E+ scenario with constrained siting availability, 2050

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 748,600 GW-km (234% increase from 2020)
- capital in service: 2,460 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)

0.002

0.002 - 52.938

52.938

0.002

17.6473

35.2927

52.938

Population Density ≤ 100 people per square km

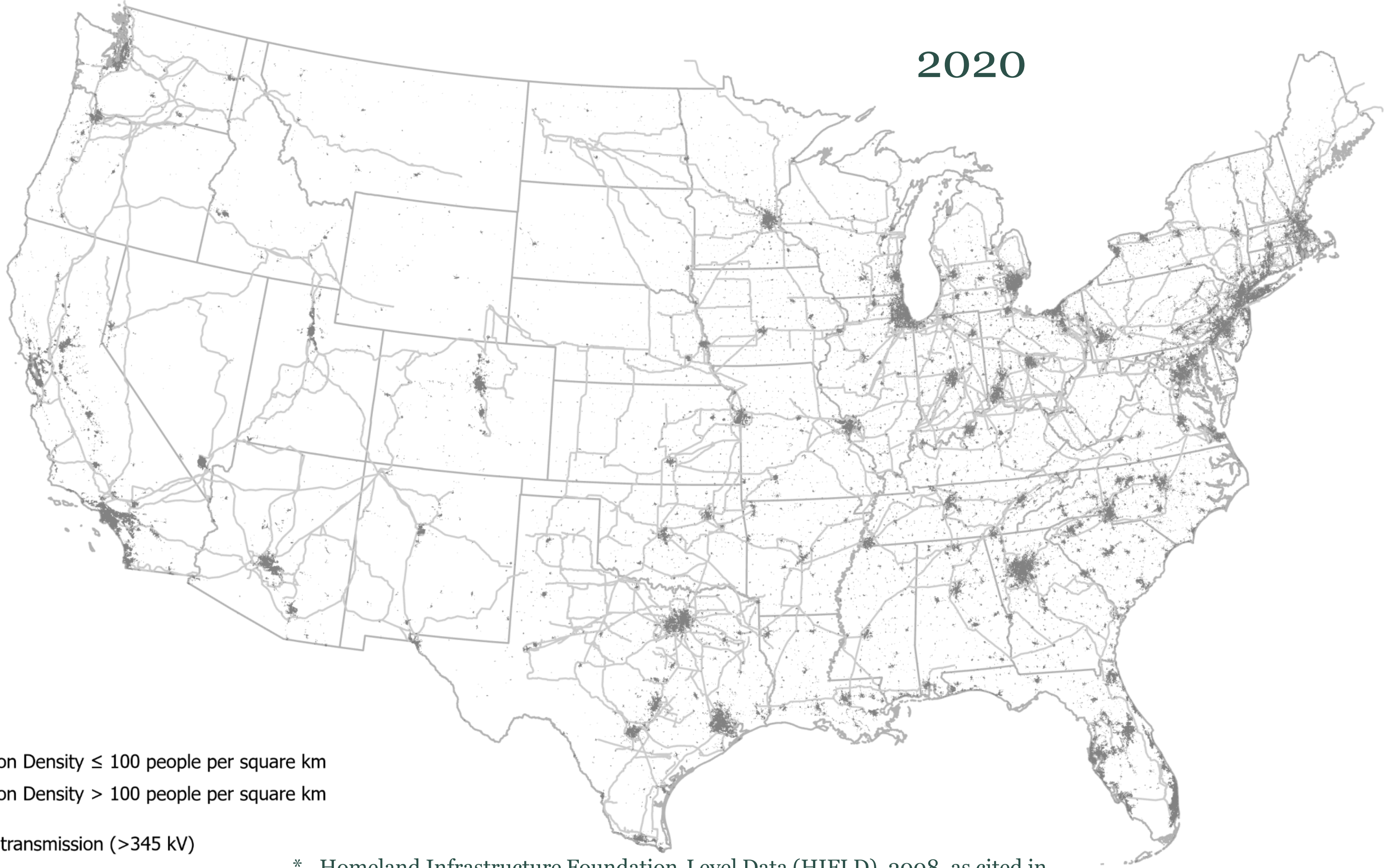
Population Density > 100 people per square km

Existing transmission (>345 kV)

Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission system in 2020 (≥ 345 kV lines shown)

Total transmission capacity:
~320,000 GW-km*



Transmission
Capacity (GW)

- 0.0000245997
- 0.0000245997 - 66.5098
- 66.5098
- 0.0000246
- 22.17
- 44.3399
- 66.5098

- Population Density ≤ 100 people per square km
- Population Density > 100 people per square km
- Existing transmission (>345 kV)

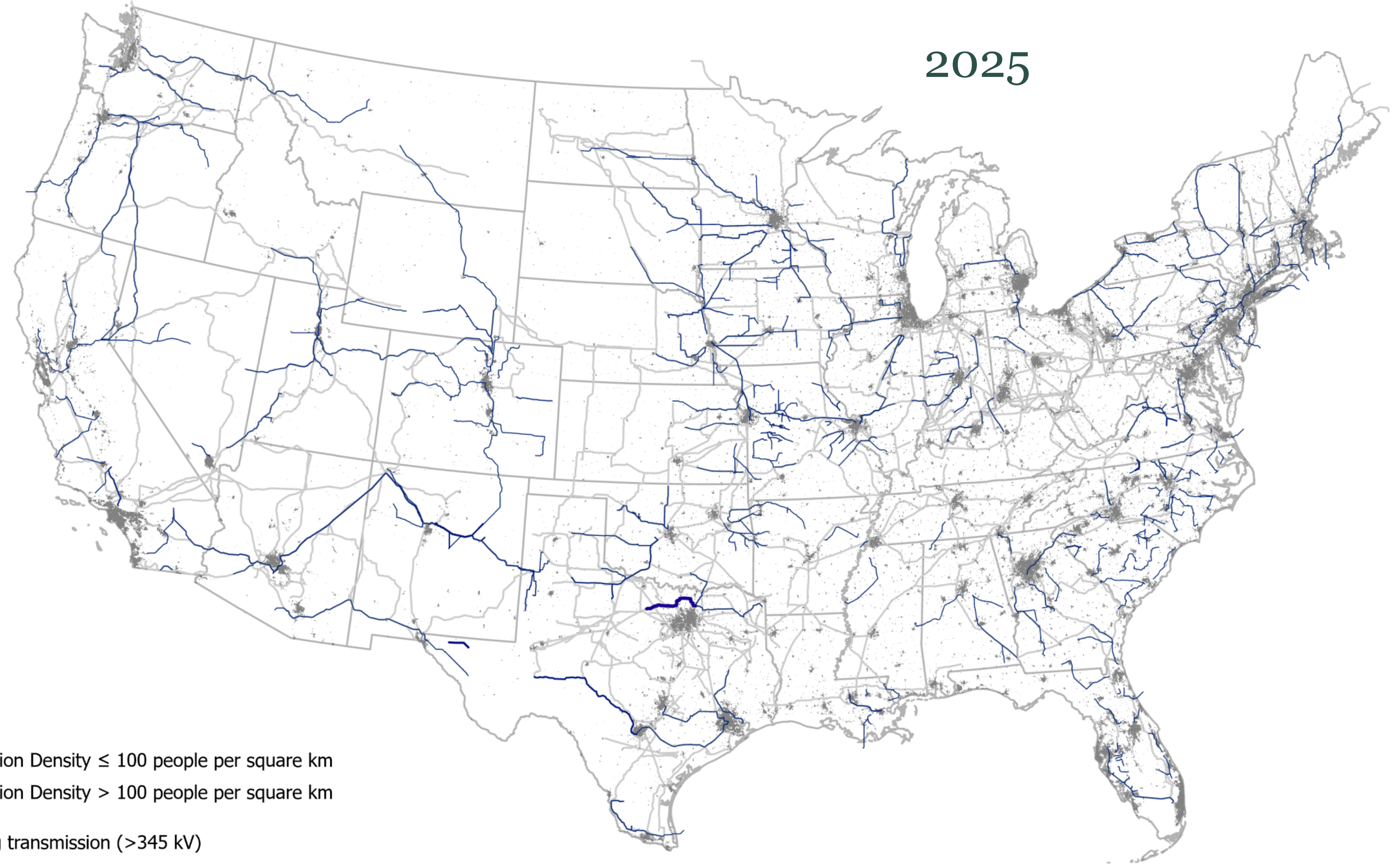
* Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.

Transmission expansions to support wind and solar generation in RE+ scenario with Base siting availability, 2025

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 94,400 GW-km (30% increase from 2020)
- capital in service: 120B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)
- 0.0000245997
- 0.0000245997 - 66.5098
- 66.5098
- 0.0000246
- 22.17
- 44.3399
- 66.5098

Population Density ≤ 100 people per square km
Population Density > 100 people per square km
Existing transmission (>345 kV)

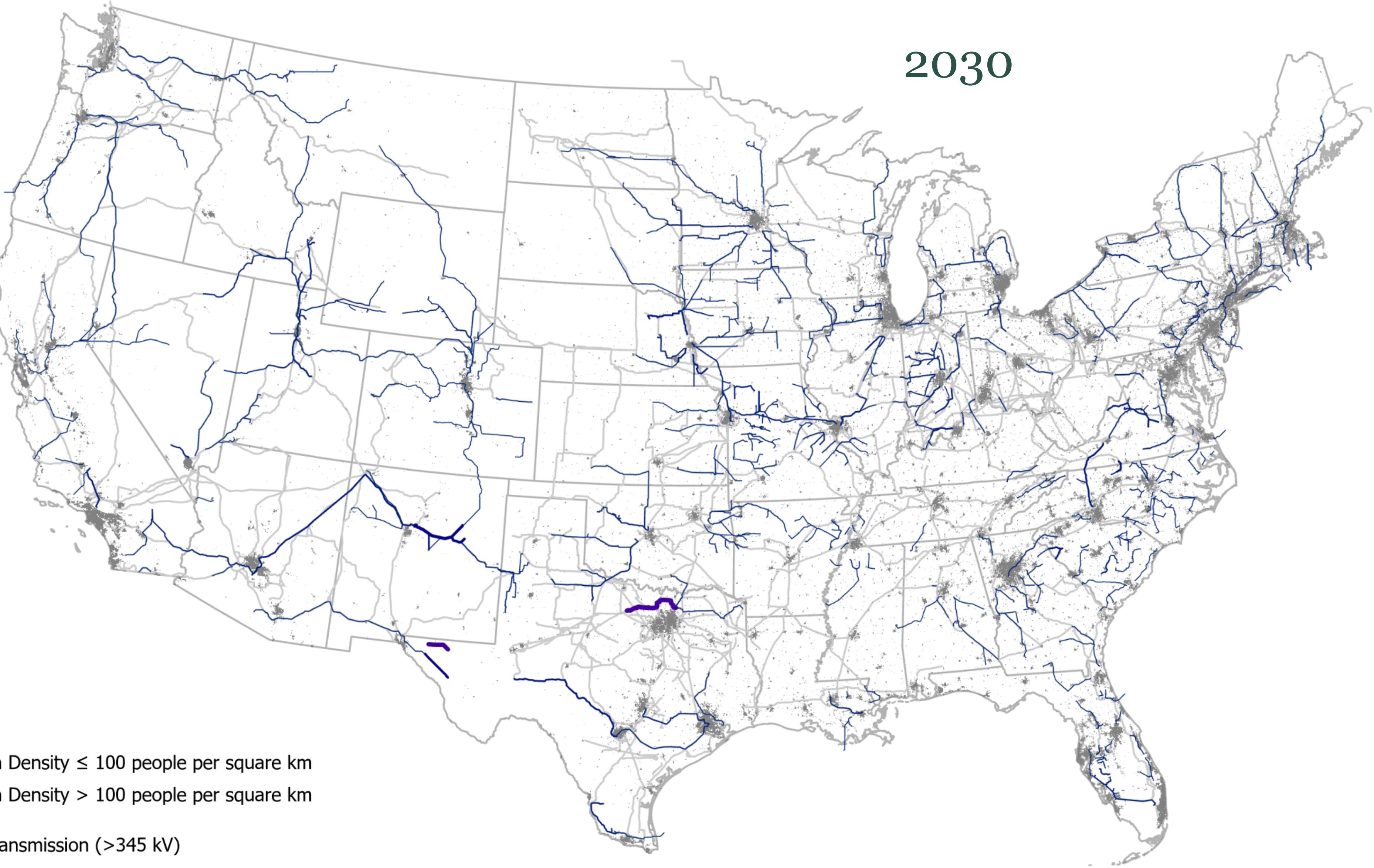
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE+ scenario with Base siting availability, 2030

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 235,400 GW-km (74% increase from 2020)
- capital in service: 320 B$

Note: Capital in service includes both capital for transmission expansions and “sustaining capital” (for end-of-life line replacements.)



Transmission Capacity (GW)

0.0000245997

0.0000245997 - 66.5098

66.5098

0.0000246

22.17

44.3399

66.5098

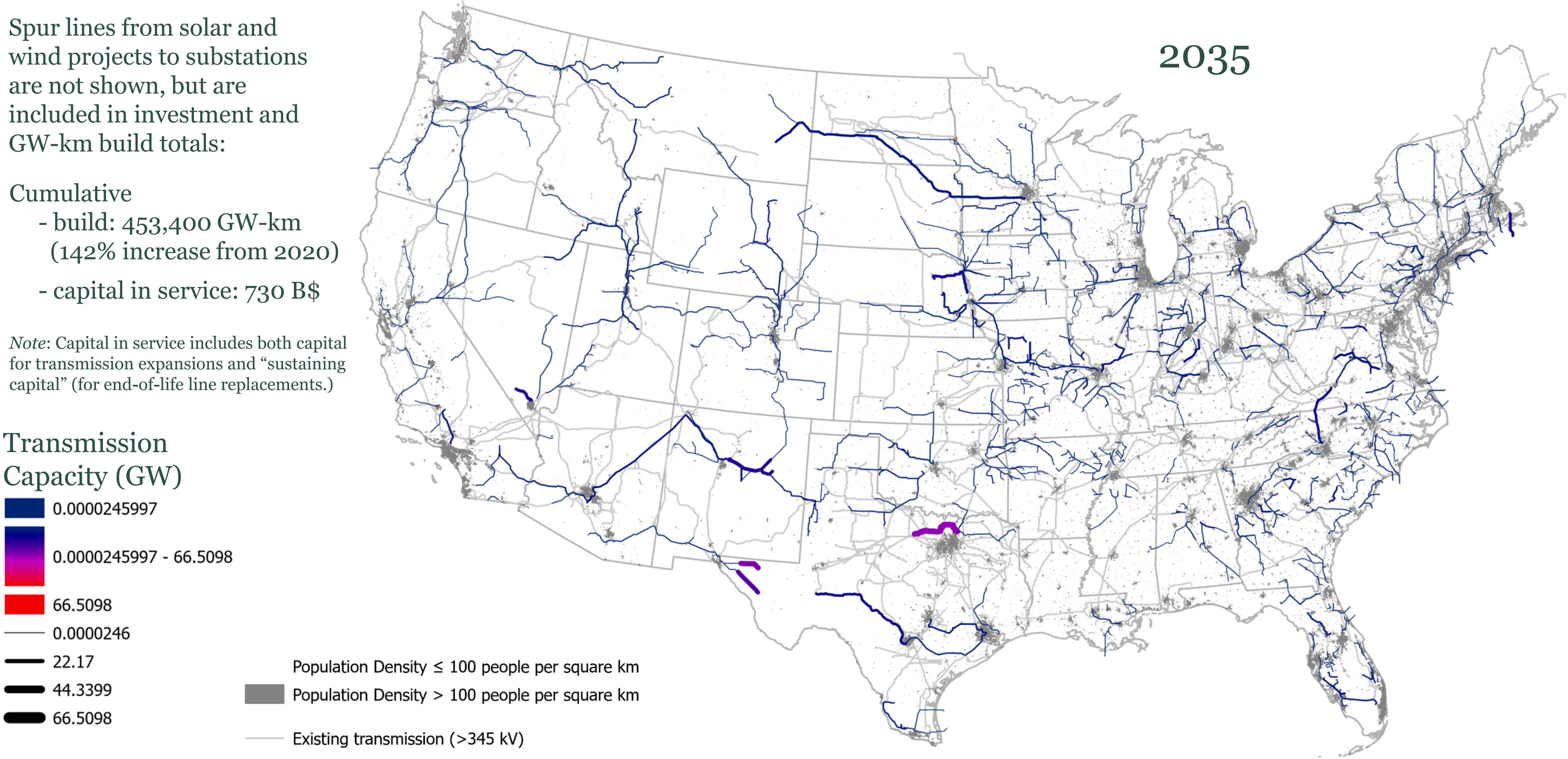
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE+ scenario with Base siting availability, 2035

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 453,400 GW-km (142% increase from 2020)
- capital in service: 730 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



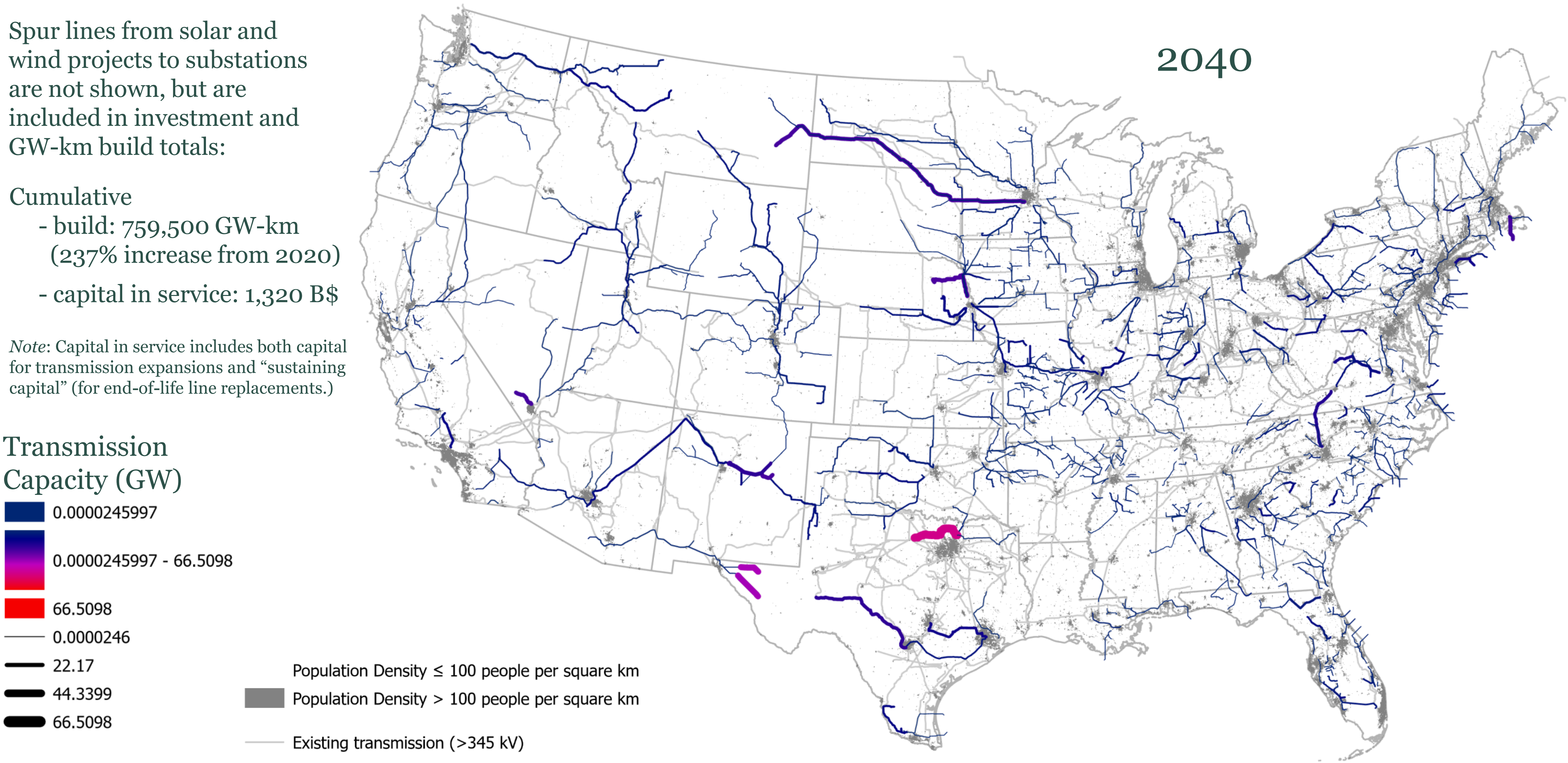
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE+ scenario with Base siting availability, 2040

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 759,500 GW-km (237% increase from 2020)
- capital in service: 1,320 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

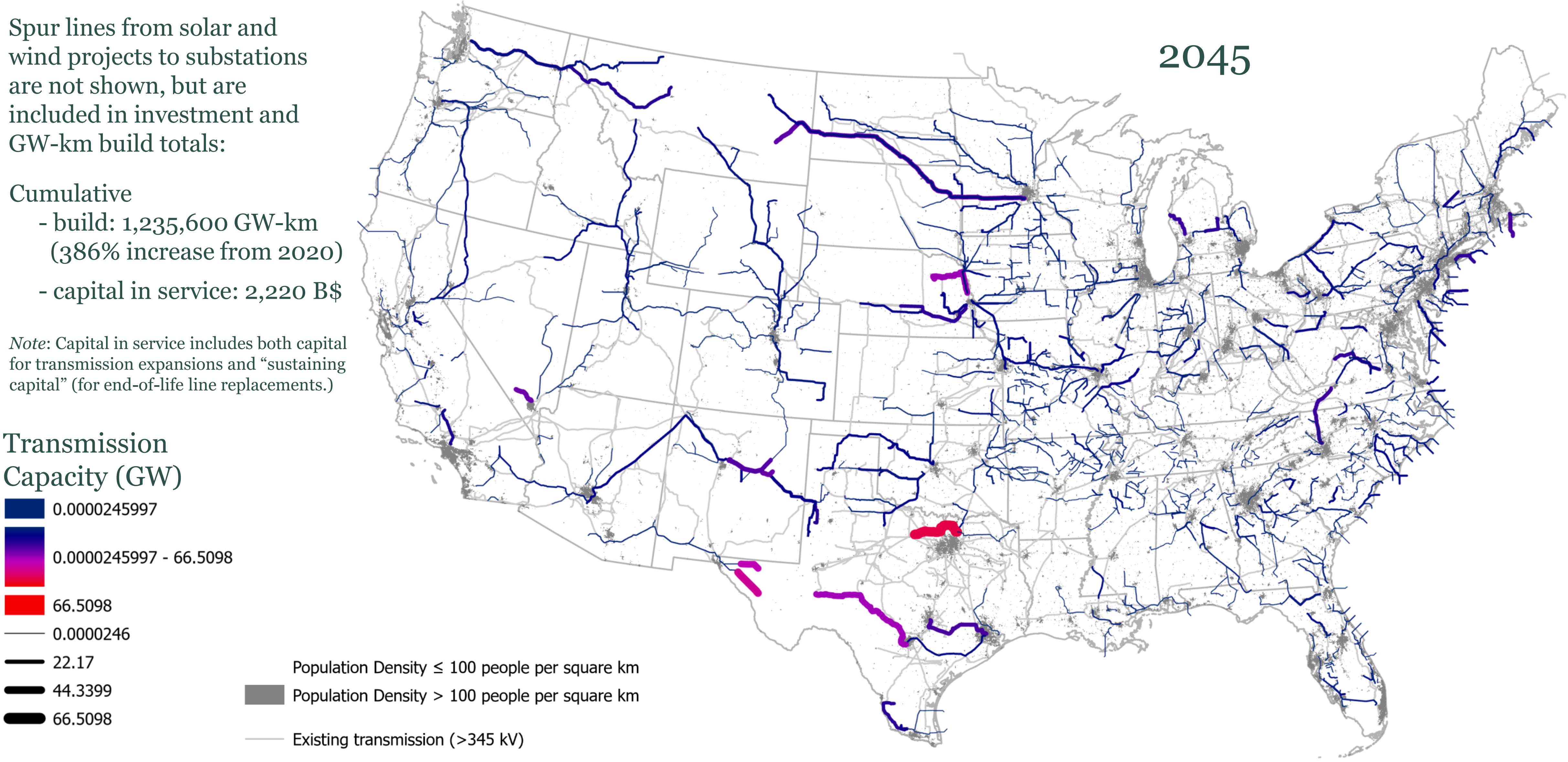
Transmission expansions to support wind and solar generation in RE+ scenario with Base siting availability, 2045

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative

- build: 1,235,600 GW-km (386% increase from 2020)
- capital in service: 2,220 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



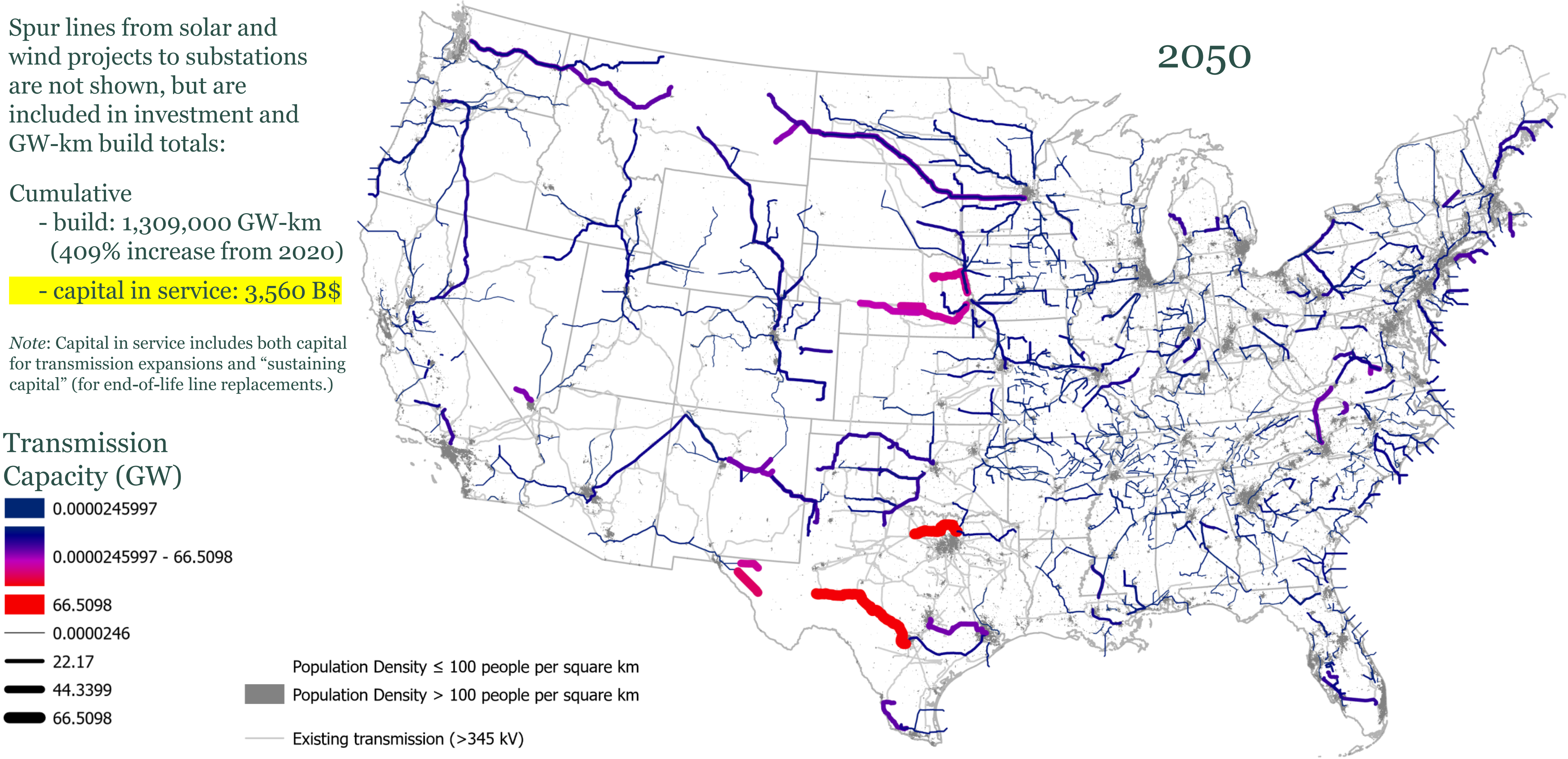
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE+ scenario with Base siting availability, 2050

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 1,309,000 GW-km (409% increase from 2020)
- capital in service: 3,560 B$

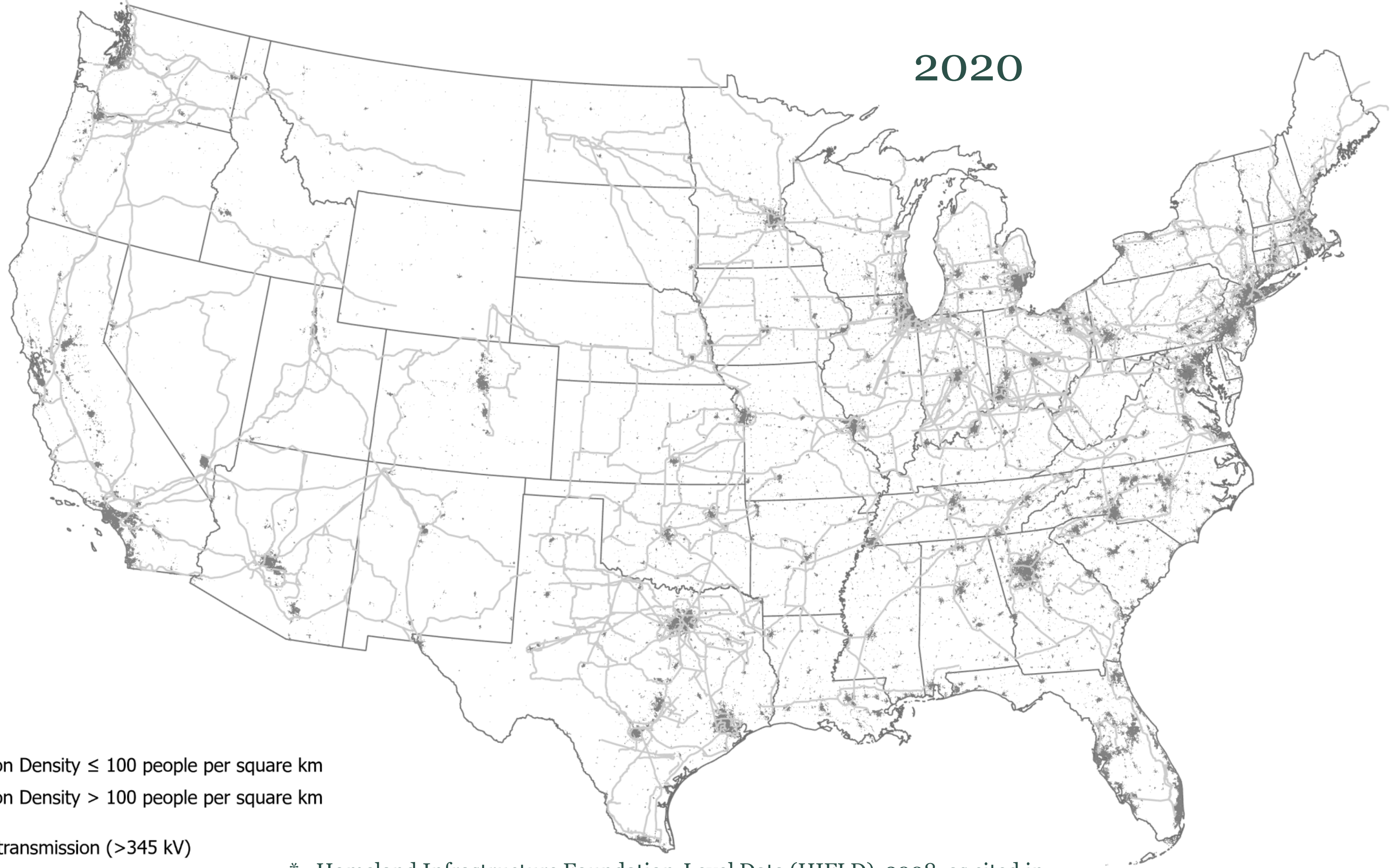
Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission system in 2020 (≥ 345 kV lines shown)

Total transmission capacity: ~320,000 GW-km*



Transmission Capacity (GW)

- 0.000512403
- 0.000512403 - 33.499
- 33.499
- 0.0005124
- 11.1667
- 22.3328
- 33.499

Population Density ≤ 100 people per square km

Population Density > 100 people per square km

Existing transmission (>345 kV)

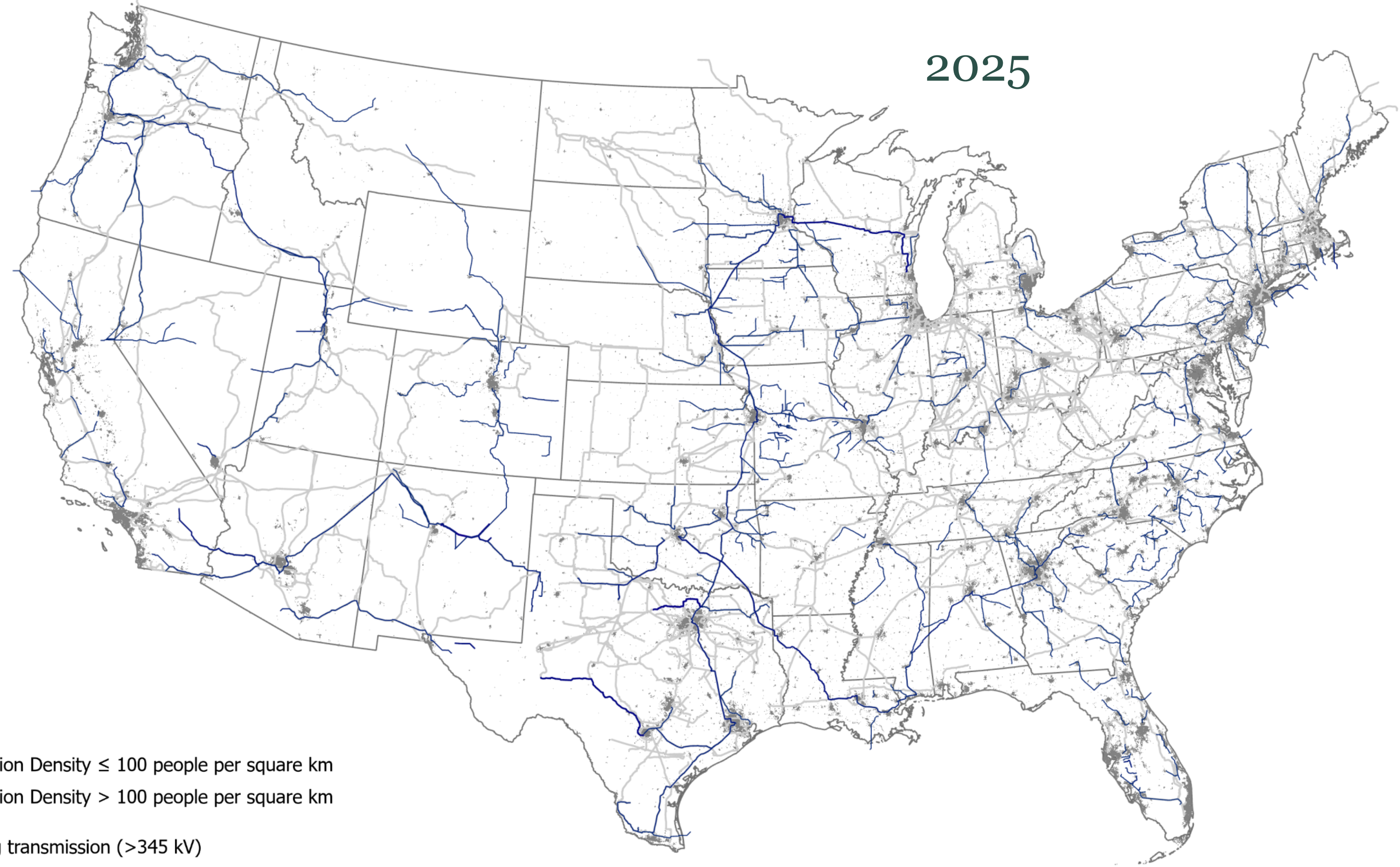
* Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, [Renewable Electricity Futures Study, 2012](#).

Transmission expansions to support wind and solar generation in RE- scenario with Base siting availability, 2025

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 82,900 GW-km
  (26% increase from 2020)
- capital in service: 130 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)

0.000512403

0.000512403 - 33.499

33.499

0.0005124

11.1667

22.3328

33.499

Population Density ≤ 100 people per square km

Population Density > 100 people per square km

Existing transmission (>345 kV)

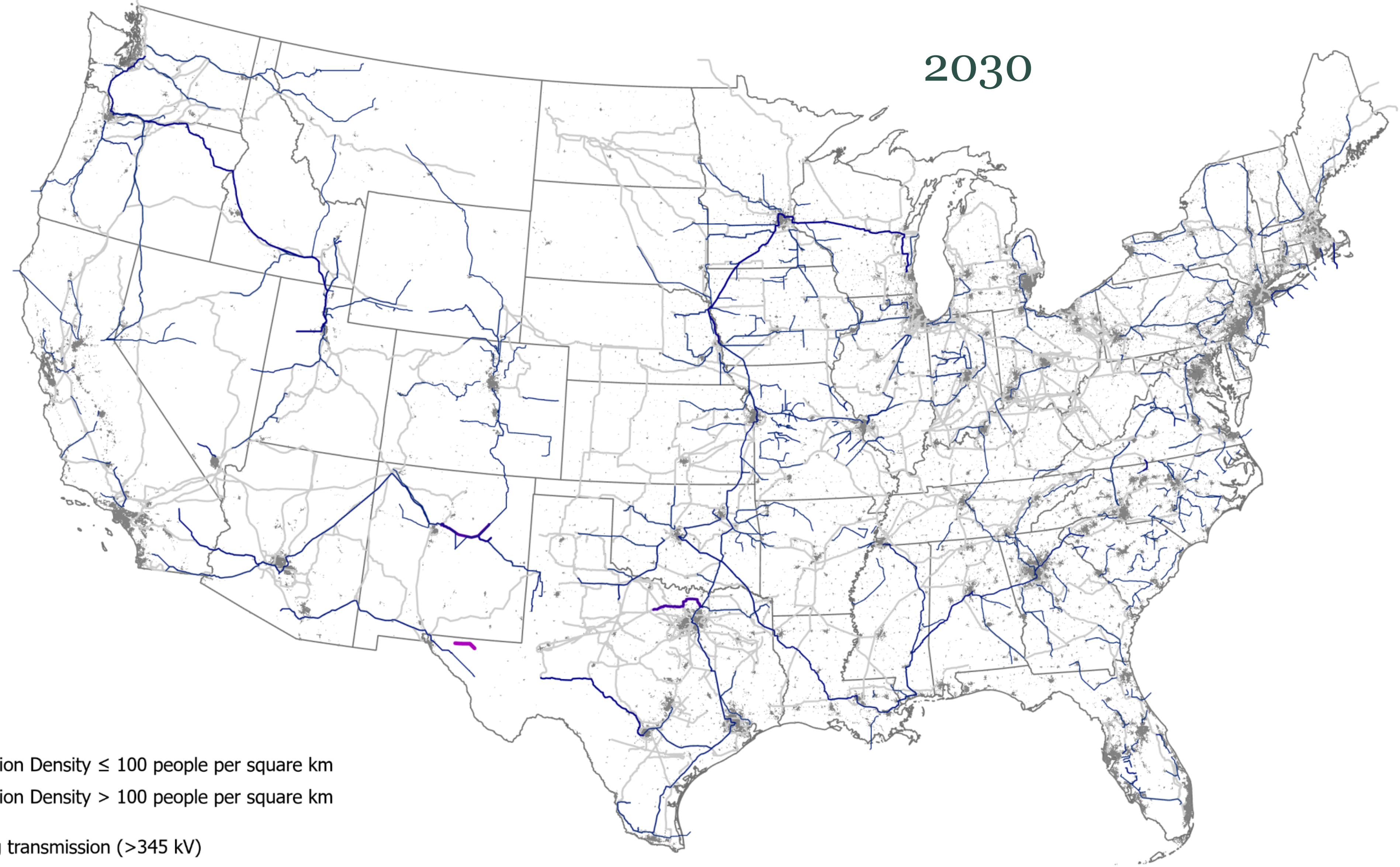
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE- scenario with Base siting availability, 2030

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 124,900 GW-km (39% increase from 2020)
- capital in service: 290 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)

0.000512403

0.000512403 - 33.499

33.499

0.0005124

11.1667

22.3328

33.499

Population Density ≤ 100 people per square km

Population Density > 100 people per square km

Existing transmission (>345 kV)

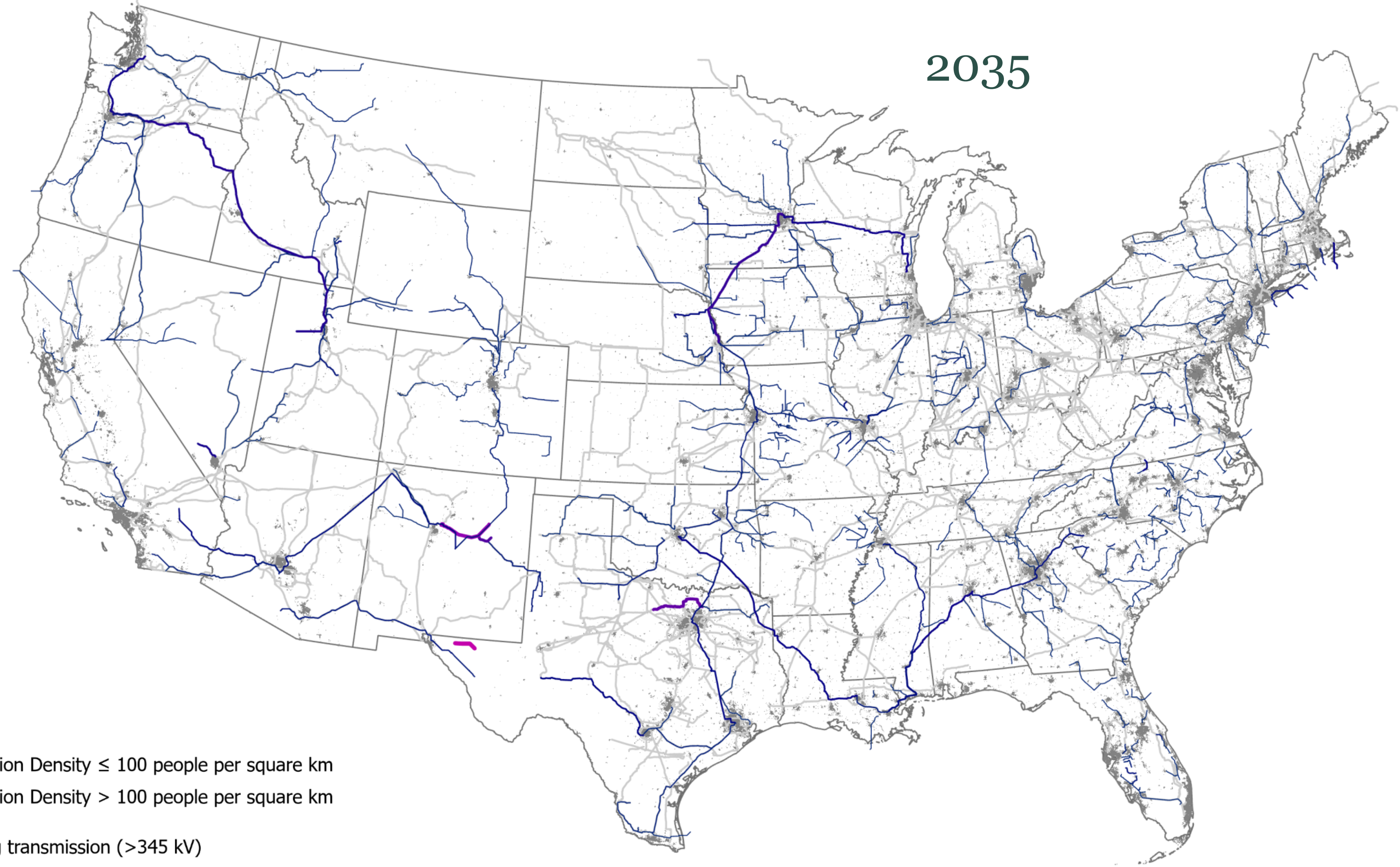
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE- scenario with Base siting availability, 2035

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 193,200 GW-km (60% increase from 2020)
- capital in service: 480 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)
- 0.000512403
- 0.000512403 - 33.499
- 33.499
- 0.0005124
- 11.1667
- 22.3328
- 33.499

Population Density ≤ 100 people per square km

Population Density > 100 people per square km

Existing transmission (>345 kV)

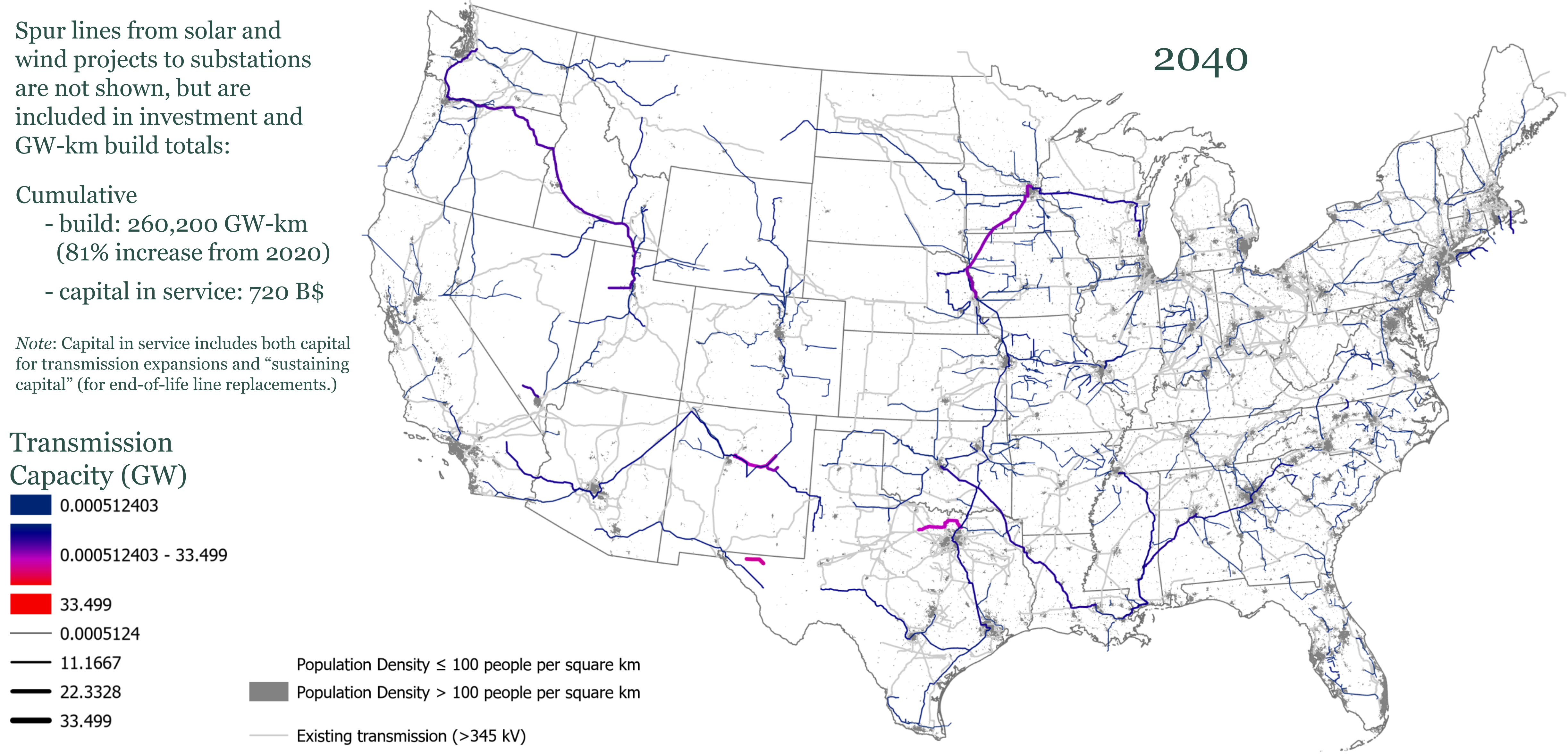
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE- scenario with Base siting availability, 2040

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 260,200 GW-km (81% increase from 2020)
- capital in service: 720 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



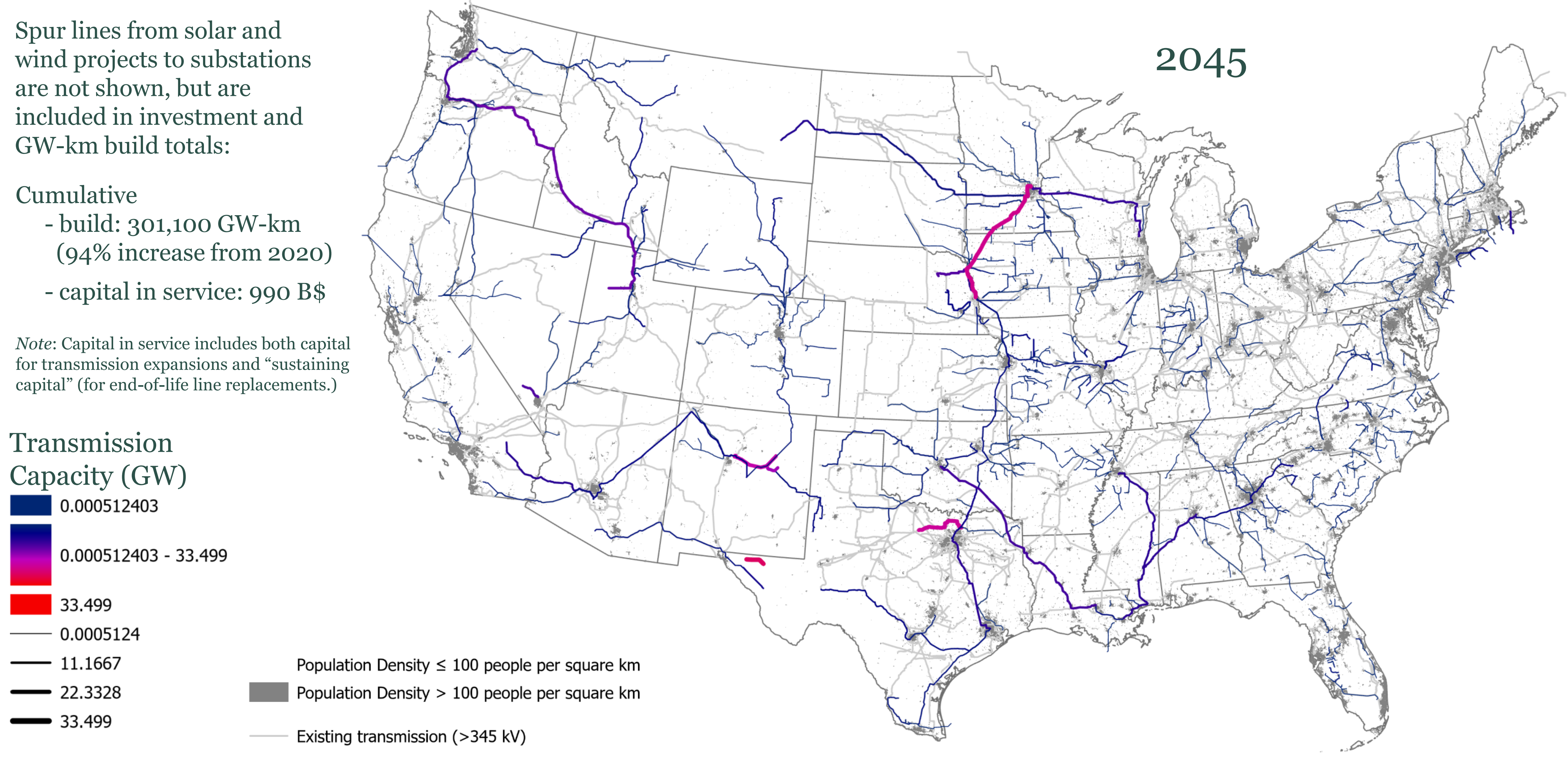
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE- scenario with Base siting availability, 2045

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 301,100 GW-km (94% increase from 2020)
- capital in service: 990 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



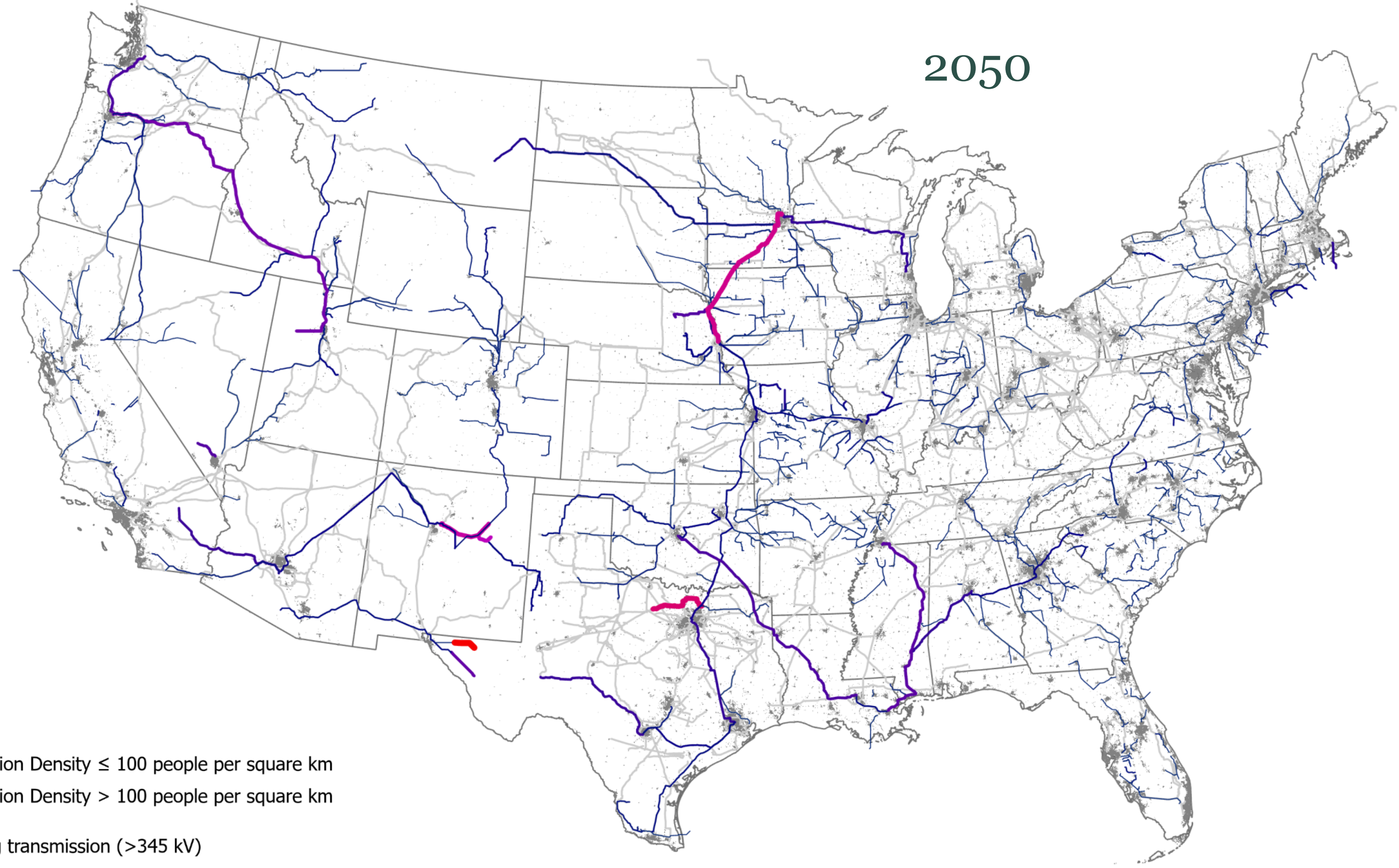
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in RE- scenario with Base siting availability, 2050

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 306,100 GW-km (96% increase from 2020)
- capital in service: 1,280 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)

0.000512403

0.000512403 - 33.499

33.499

0.0005124

11.1667

22.3328

33.499

Population Density ≤ 100 people per square km

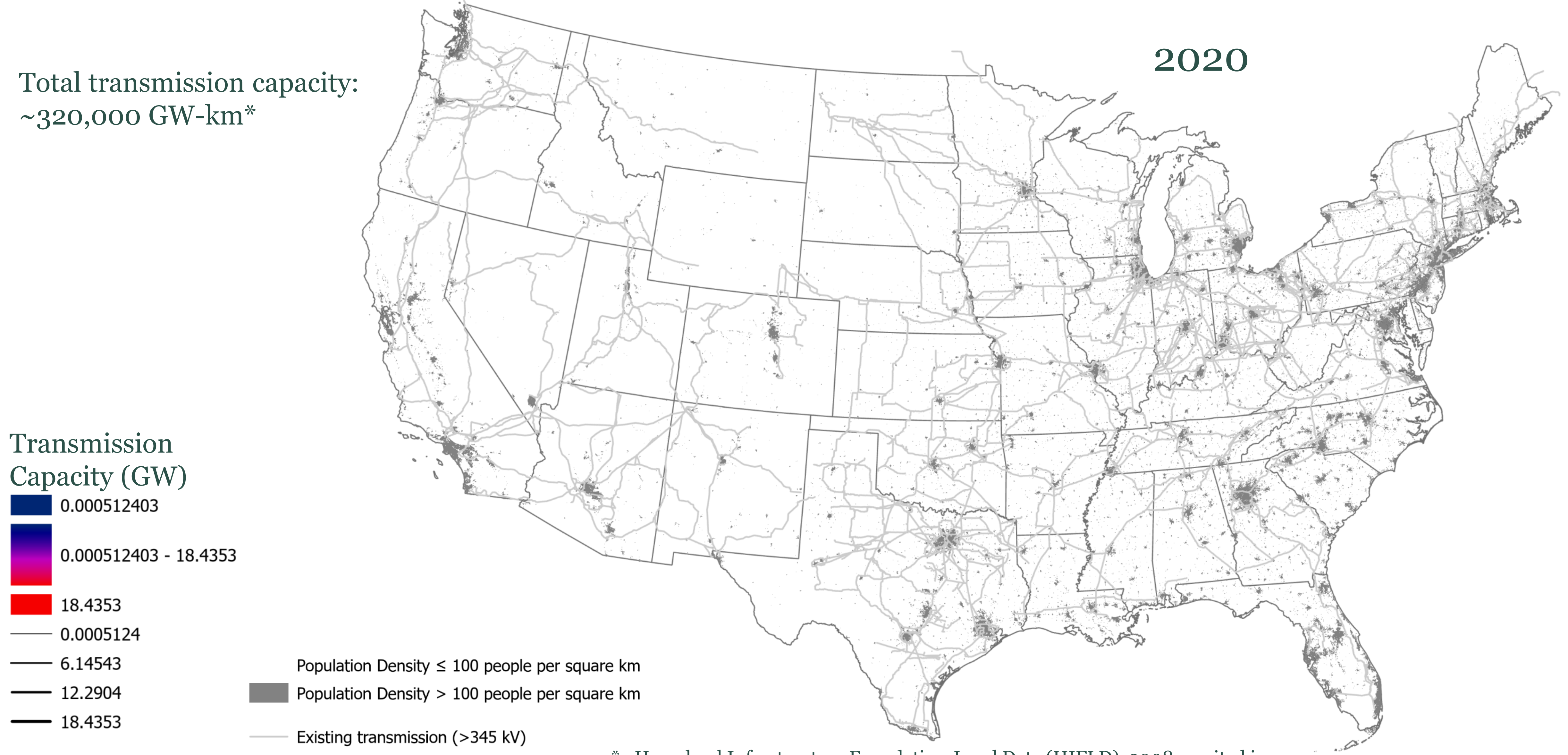
Population Density > 100 people per square km

Existing transmission (>345 kV)

Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission system in 2020 (≥ 345 kV lines shown)

Total transmission capacity:
~320,000 GW-km*



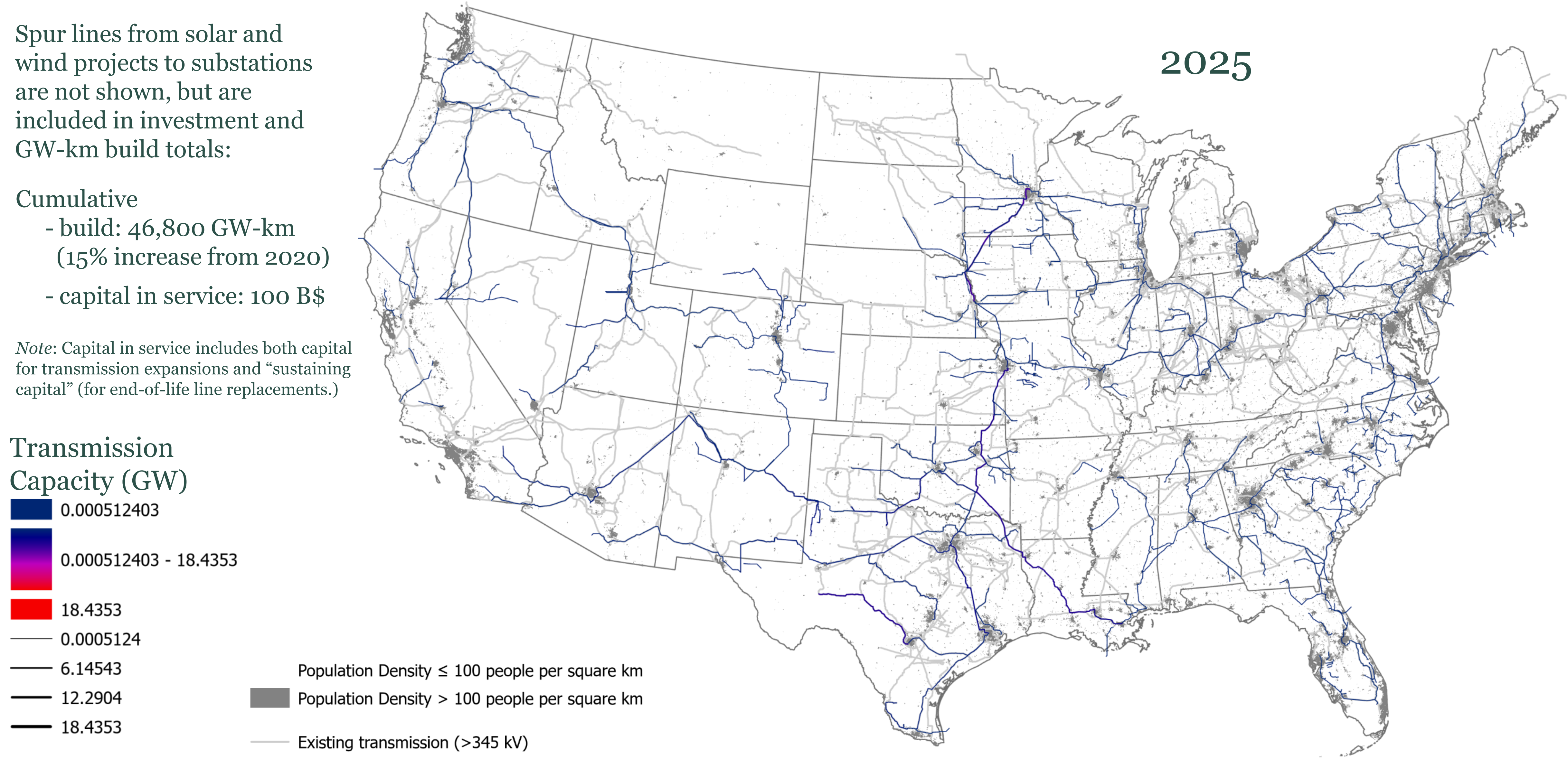
* Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.

Transmission expansions to support wind and solar generation in REF scenario with Base siting availability, 2025

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 46,800 GW-km (15% increase from 2020)
- capital in service: 100 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



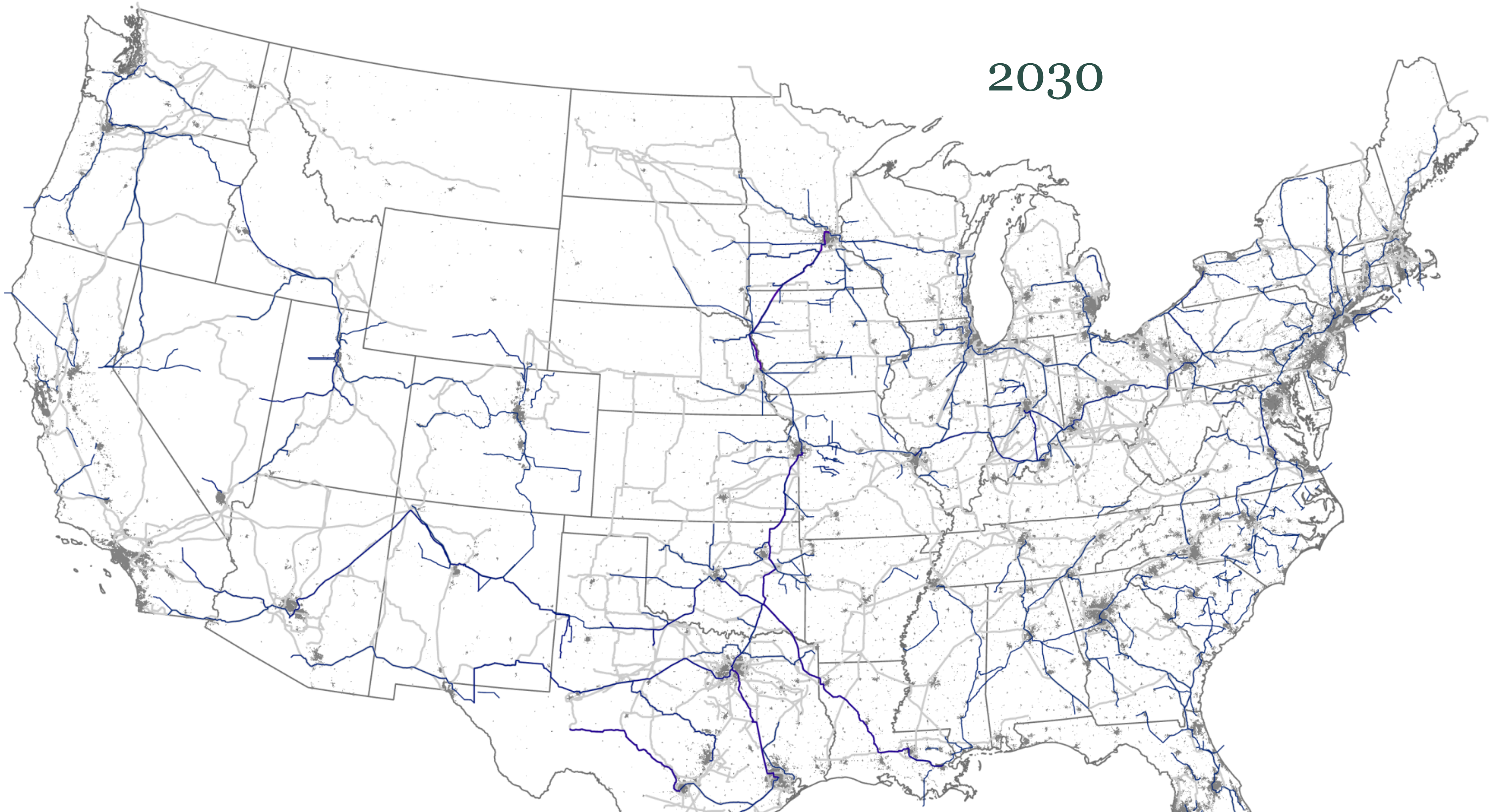
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in REF scenario with Base siting availability, 2030

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 58,900 GW-km (18% increase from 2020)
- capital in service: 210 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)

0.000512403

0.000512403 - 18.4353

18.4353

0.0005124

6.14543

12.2904

18.4353

Population Density ≤ 100 people per square km

Population Density > 100 people per square km

Existing transmission (>345 kV)

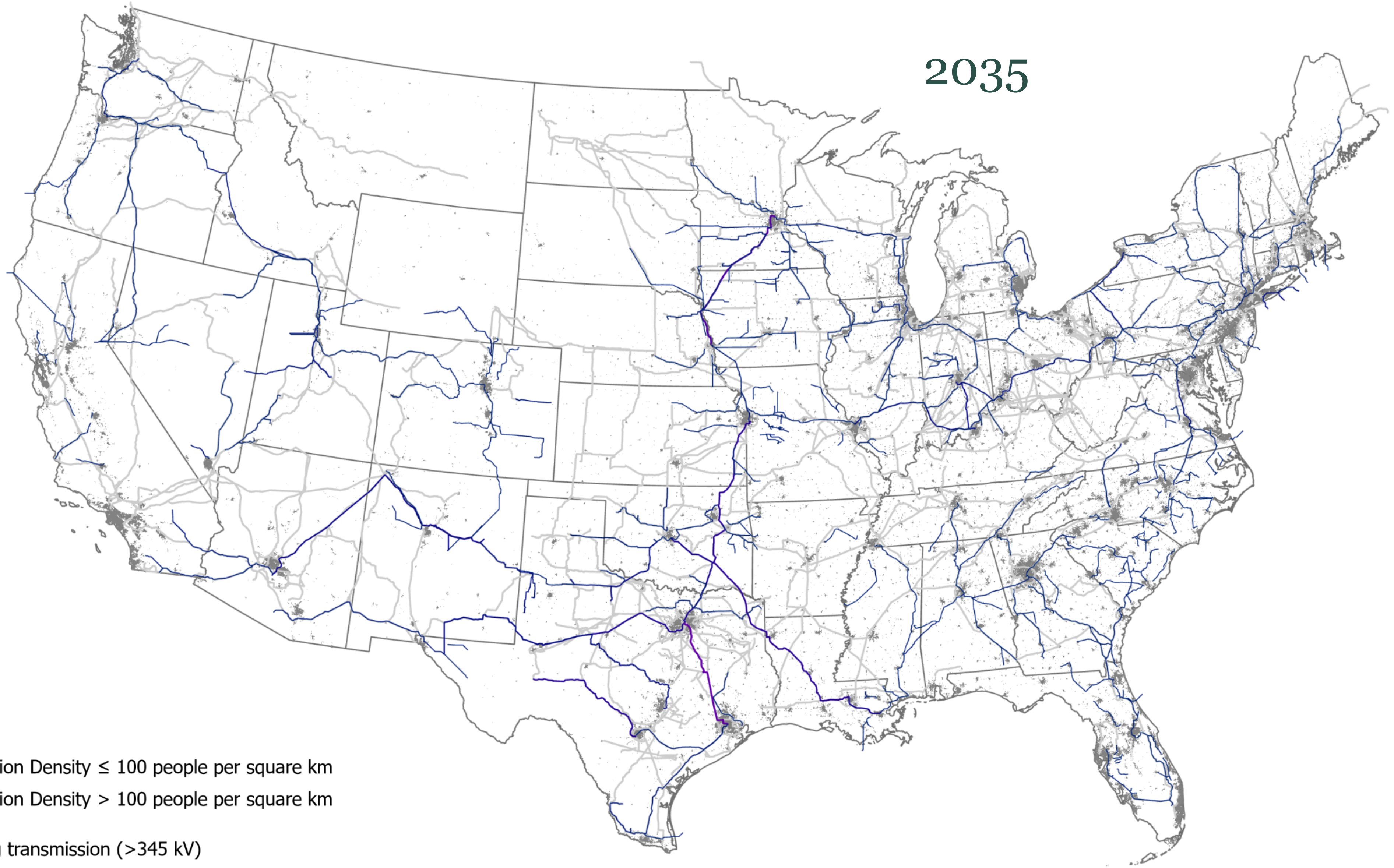
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in REF scenario with Base siting availability, 2035

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 96,400 GW-km (30% increase from 2020)
- capital in service: 340 B$

Note: Capital in service includes both capital for transmission expansions and “sustaining capital” (for end-of-life line replacements.)



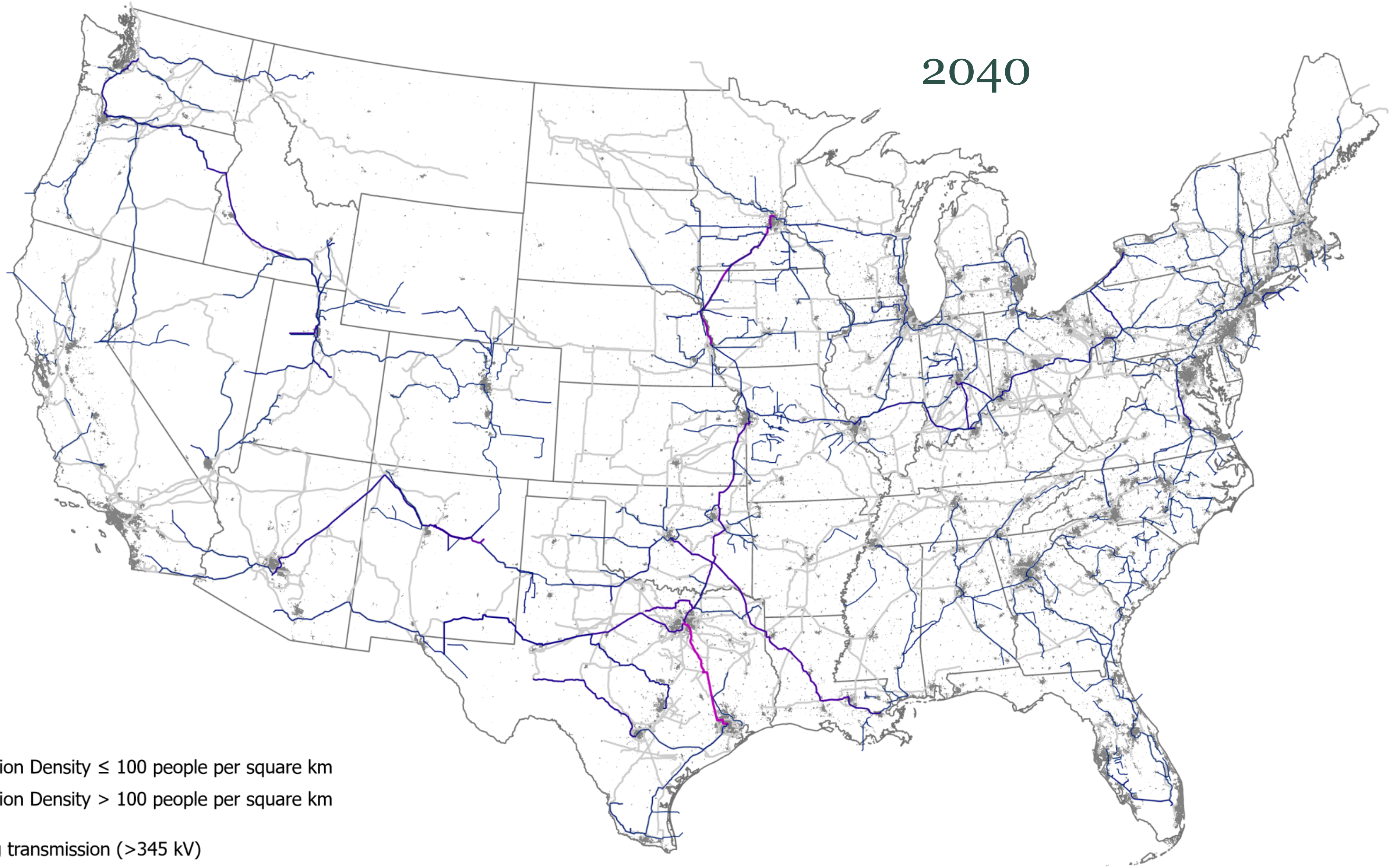
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in REF scenario with Base siting availability, 2040

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 122,100 GW-km
  (38% increase from 2020)
- capital in service: 510 B$

Note: Capital in service includes both capital for transmission expansions and “sustaining capital” (for end-of-life line replacements.)



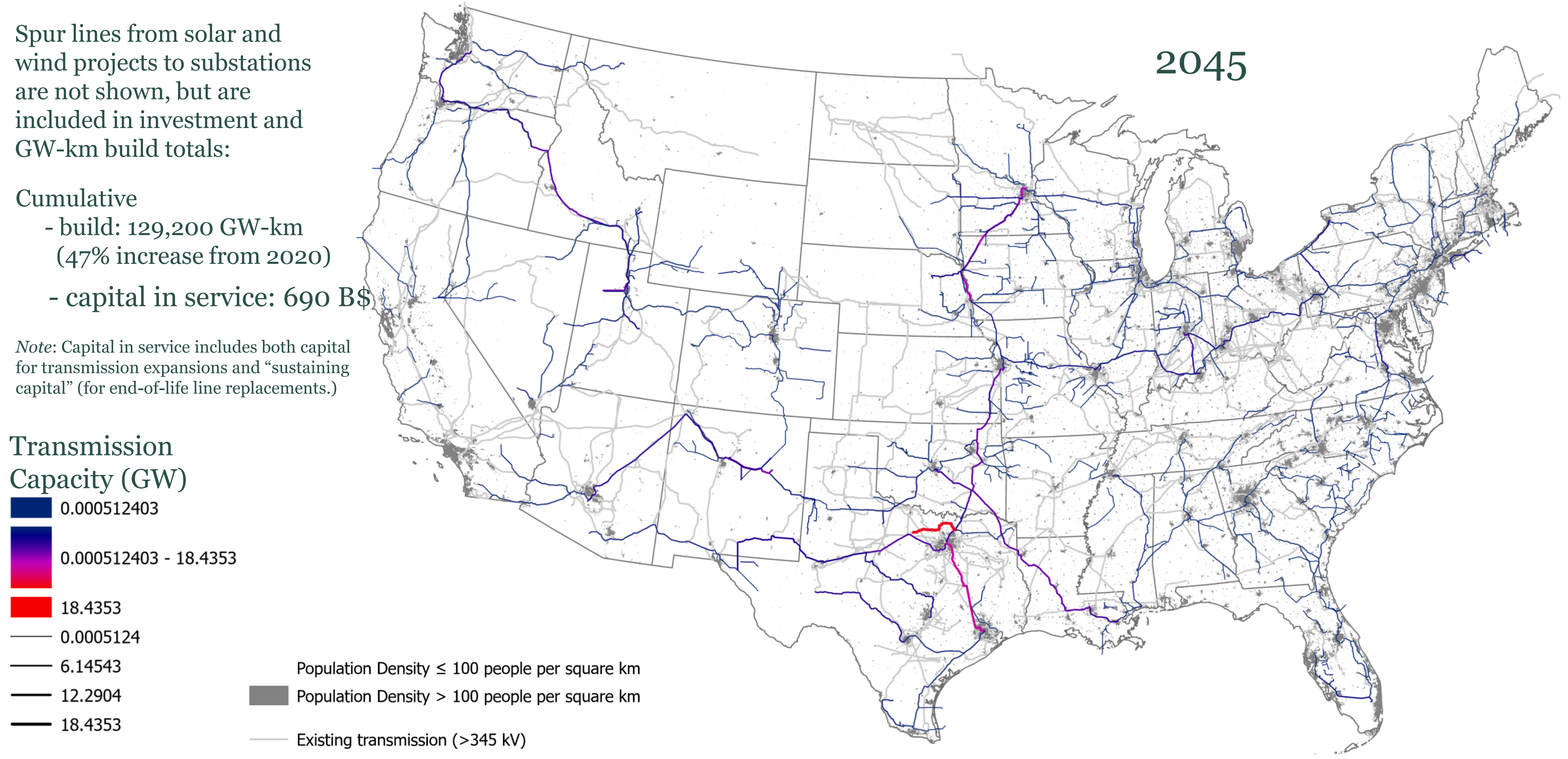
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in REF scenario with Base siting availability, 2045

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 129,200 GW-km (47% increase from 2020)
- capital in service: 690 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



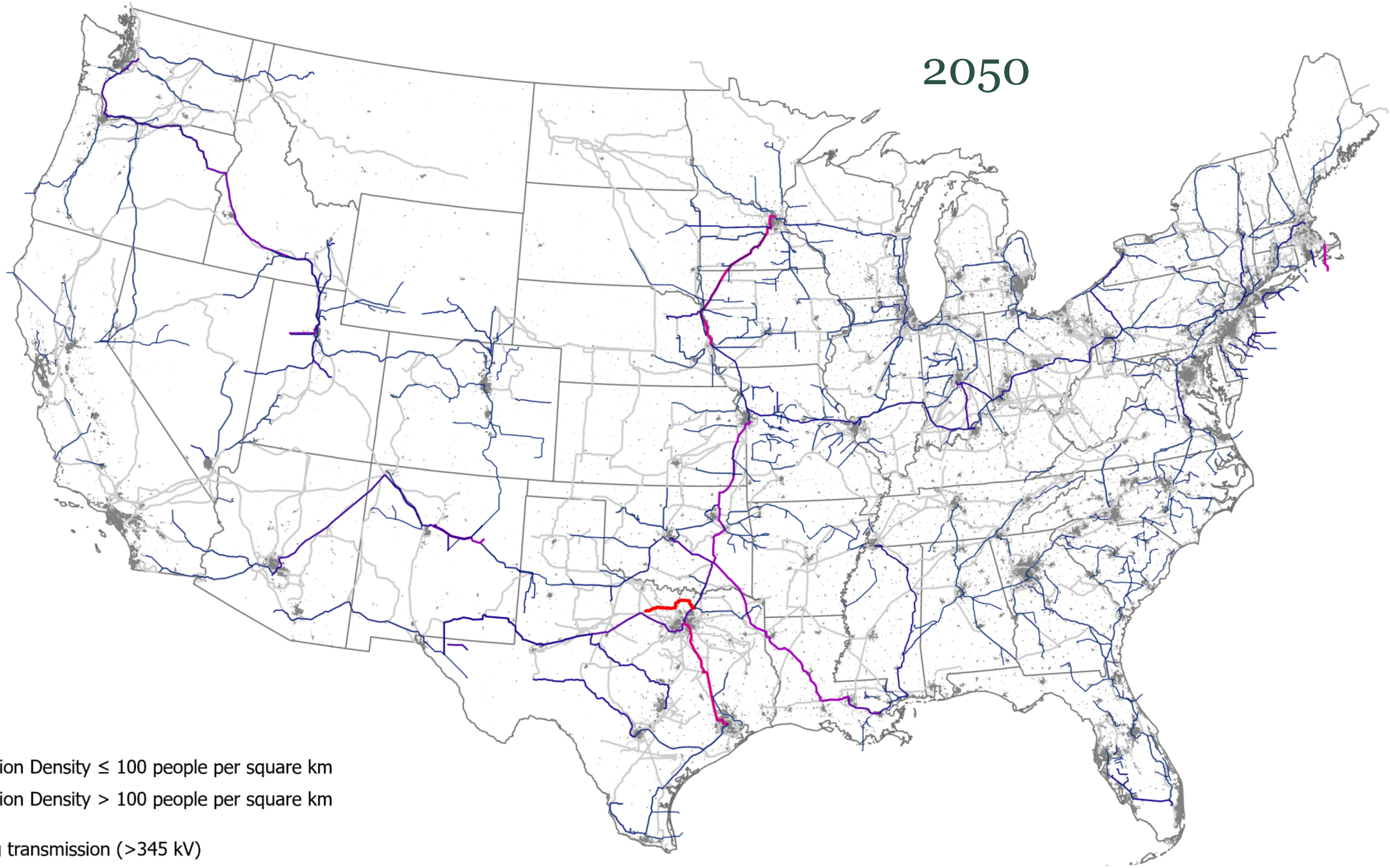
Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.

Transmission expansions to support wind and solar generation in REF scenario with Base siting availability, 2050

Spur lines from solar and wind projects to substations are not shown, but are included in investment and GW-km build totals:

Cumulative
- build: 151,700 GW-km (47% increase from 2020)
- capital in service: 945 B$

Note: Capital in service includes both capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Transmission Capacity (GW)

0.000512403

0.000512403 - 18.4353

18.4353

0.0005124

6.14543

12.2904

18.4353

Note: Transmission expansion is visualized along existing rights of way (>160 kV); paths are indicative not definitive.