The Ray Solar Highway Project:

Assessment of solar potential installed in ROWs across the United States

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2020

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Executive Summary

Key Takeaways

- Most states have more than 200 miles of interstate frontage suitable for solar PV development, totaling over 127,500 acres of ROW area.
- We estimate that placing solar at interstate exits could generate up to 36 TWh per year (about 1% of total usage in the U.S.) and provide about $4 billion in economic value to State DOTs.
- Stretches of ROW along interstates and between interchanges are generally too narrow to allow for installation of solar PV while meeting FHWA safety guidelines for shoulder and clear area zones.
- Because they have more room to accommodate the transportation safety requirements, interchanges (i.e., butterfly or diamond-shaped interchanges) and rest areas have the most potential for installation of solar PV.
- Federal law and some regulations limit use of ROW areas that lack “secondary access,” including some interchanges.
- Some State DOTs do not have publicly available full spatial ROW data sets, which is a barrier to a specific analysis of rest areas and interchanges for installation of solar PV - including this analysis, which <u>excludes</u> all rest areas in the U.S.
- States considering ROW solar projects should first develop full spatial ROW data sets that can be used to find the most appropriate locations.

State departments of transportation (State DOTs) own and/or maintain significant amounts of land in the right-of-way (ROW) along existing interstate highways. These ROW areas are appealing energy development locations for many reasons including: location and proximity to the nation’s electricity grid, ease of access, public ownership status, lack of competing development efforts, and the potential for State DOTs to reduce operating and maintenance costs, and potentially create new revenue streams. However, federal law and some Federal Highway Administration (FHWA) regulations limit renewable energy infrastructure in ROW areas that lack “secondary access,” which is site access other than the interstate lanes themselves. The aim of this project is to provide a report and web tool by which State DOTs or other interested parties can assess the potential for installation of solar PV in ROW areas associated with interstates in the contiguous 48 states within the United States (U.S.). Additionally, outcomes from this project can help suggest improvements and changes to existing regulations and data collection methods, to inform and facilitate expanded development of solar PV and other renewable energy options in the ROW areas. This report and related documents, data products, and web tool are meant to be used as a resource for State DOTs and other interested parties in the selection of ROW sites with potential for solar photovoltaic (PV) development.

Unfortunately, available data of exact ROW boundaries with sufficient detail to be useful for the analysis are very limited. To the best of our knowledge, Iowa was the only state to have sufficiently detailed public ROW data available. There is a critical and immediate need for State DOTs to develop full spatial ROW data sets. To address the data gap, a methodology based on the case study of Iowa was developed and applied to the remaining states. Because of the limited resolution, those results should be considered preliminary until higher-quality information on ROW is available.

Google Earth analysis tools were used to measure the available area along ROWs with potential for solar installations. Results from this analysis showed that long, narrow stretches of interstate (the majority of ROW areas) do not have sufficient width available outside of transportation safety requirements (such as the FHWA safety guidelines for shoulder and clear area zones) to allow for solar PV installations. However, there are suitable sites. Namely, interchanges, rest areas, and other large tracts of open ROW land that have beneficial attributes such as easy access, unshaded acreage, and increased depth, all generally without competing land uses.

Given the lack of available ROW data, the web tool is limited to interstate interchanges because these areas can be identified visually or via machine-learning using available data. Rest areas and other large tracts of ROW are not included in the web tool, but certainly should be analyzed and considered for solar PV development as data sets become available. Interchange type and quantity, as well as expected solar potential and monetary electricity value were estimated using a custom developed interchange identification and classification tool. Because there are likely to be additional ROW areas available within each state, these results, which are limited to interchanges, present a conservative estimate of solar potential in ROW for all states. States considering ROW solar projects are strongly encouraged to concurrently develop full spatial ROW data sets that can be used to find the most appropriate locations.

Even after restricting the analysis to interstate interchange locations, most states have more than 200 miles of suitable interstate frontage remaining, totaling between 440 and 6,600 acres of ROW area (depending on the state) in interchanges available for solar installation. Due to variations in retail electricity prices and solar capacity factors, as well as total area available by state, there is significant variability in the estimated solar potential and electricity value across states. However, most states have solar potential in the thousands of GWh per year (127 to 1,814 GWh, depending on the state) with an estimated value of several hundreds of millions of dollars of prospective revenue to the state. At a typical retail price for electricity of ~$0.10/kWh and a wholesale price of ~$0.02/kWh, this means states could potentially generate low-carbon electricity with a value of millions to tens of millions of dollars ($2.5 to $181.4 million/year, depending on the state) and non-trivial royalties to State DOTs over the lifetime of the project.

Introduction

Development of renewable resources in available area within the right-of-way (ROW) of interstates within the United States (U.S.) has the potential to help states reduce energy and land maintenance costs, increase revenue to state Departments of Transportation (State DOTs) without raising taxes, as well as increase local energy security and meet renewable energy and greenhouse gas emission reduction targets. Due to its flexibility in sizing and limited environmental impacts, solar photovoltaic (PV) systems are an attractive option for installation in existing ROWs. Several states, including Georgia, Massachusetts, and Oregon have already implemented such 'solar highway' projects. Solar highway projects are also common in Europe[1].

In Oregon, two different sites with 1.85 MW total solar capacity have been installed in existing ROW. The larger of the two sites, the Baldock Solar Station, is a 1.75 MW array installed at an existing rest area. This station went into service in 2012 and is a public-private partnership with Portland General Electric [1]. Massachusetts' solar project consists of eight different site locations with a total installed capacity of 4.3 MW [2]. Maryland DOT (MDOT) has 1.8 MW installed solar capacity over five sites. Based on the success of these projects, MDOT developed a DOT-wide solar program and conducted a comprehensive analysis of its statewide inventory of facilities to determine locations that can accommodate solar PV systems. The program includes a master services agreement that prequalified six Master Contractors to secondarily compete to install solar PV systems on MDOT properties throughout the State. The Master Contractors are responsible for constructing, owning, operating, and maintaining the PV systems infrastructure for the entire term of the agreement (20-25 years). MDOT will either buy the power generated or will charge the Master Contractor a land fee and the energy will be fed to the grid. MDOT will not expend any upfront capital funds for the development of solar PV infrastructure.

In February 2019, Georgia Power began operating a 1 MW solar array in the ROW area of Interstate 85, located at exit 14 in one five-acre quadrant of a diamond interchange on "The Ray." This project involved a broad partnership of public and private sector partners, including the philanthropy of The Ray, and is unique in the layers of benefit that it returns to the Eisenhower Interstate System. Georgia Power installed and will operate nearly 50 high mast LED lights at the exit, which was previously unlit, to contribute to the safety and navigation of the stretch of interstate. The solar PV on the ROW of The Ray also incorporates pollinator habitat and serves as a testing ground for emerging technologies that can inform future projects in Georgia and across the country [3].

Several important considerations for the development of solar highway projects have been learned from these pilot projects. Logistics of siting solar arrays in ROWs must manage concerns of interstate safety, available space, federal regulations for ROW use, as well as solar potential at the site. Additionally, some State DOTs may be averse to taking on the risks or burden of up-front capital costs. As government agencies, State DOTs cannot take advantage of the available financial tools, such as available tax credits for renewable energy, the federal investment tax credit, and modified accelerated depreciation and cost recovery [1] [2] [3].

The goal of this project is to provide a first-ever assessment of ROW areas on the U.S. interstate system that are available and present the potential for solar PV installation, given the data sets available from State DOTs. A web tool was developed which identifies the existing and most easily-identifiable ROW interstate interchange locations that might be viable for solar PV, excluding rest areas, and provides estimates of potential electricity generation and monetary value of that generation at these locations. This undertaking is a starting point for further, detailed analysis of potential locations for solar PV siting and development, and the web tool can be updated as full spatial ROW data sets are provided by State DOTs, including data sets that include rest area acreage.

1 https://www.solarhighways.eu/en/about-solar-highways

Additionally, outcomes from this project illustrate that certain long-standing policies and requirements, such as the FHWA requirement for “secondary access,” restrict development of solar PV in ROW areas that otherwise have significant potential.

This report and related documents, data products, and web tool are a unique resource for State DOTs and other transportation entities to aid in the selection of ROW sites with potential for PV solar development, and in securing any necessary authorizations for PV solar programs and projects in the ROW.

DOT Solar Revenue Pathways

The Federal Highway Administration (FHWA) allows State DOTs to accommodate the development of renewable energy generation projects in the ROW, and established pathways for State DOTs to seek and receive federal authorization in a 2009 memorandum titled “Guidance on Utilization of Highway Right-of-Way,” a subsequent report and quick guide[2]. These FHWA resources lay out two pathways available for solar PV accommodation in ROW areas: 23 CFR part 645, allowed as an activity under a State DOTs approved utility accommodation policy (UAP), for projects that meet the public test and are thus not subject to limits on commercialization, and; 23 CFR part 710, as a ROW Use Agreement reserved for private, proprietary projects.

23 CFR part 645 allows a state to use an approved UAP to install solar PV in the ROW without referral to FHWA for approval of the project if the state includes renewable energy in its definition of utility facility, and the project serves the public. Utility projects such as these that meet the “public test” are not subject to long-standing federal law limiting commercial activity on the interstate ROW. Project approval by FHWA is not required if the solar PV installation is in alignment with 23 CFR 645 or the approved UAP. The UAP does not need to specifically address renewable energy facilities to accommodate a solar PV installation. The project meets the public test requirement if the energy offtaker is the DOT, another public agency, the utility, or a community solar program.

23 CFR 710 uses Right-of-Way Use Agreements to install solar PV in the ROW if state law excludes renewable energy from its definition of utility facility, or if the project does not serve the public. Project approval by FHWA is required, and FHWA must determine if the project is in the public interest. If Title 23 funds were used to acquire the ROW, fair market analysis must be conducted, and a fair market rent must be collected for use of the ROW. The project generally does not meet the public test if the energy offtaker is solely a private entity.

FHWA generally requires a Fair Market Value (FMV) analysis for projects seeking accommodation under a ROW Use Agreement to proceed. Land valuation of the interstate roadsides can be a challenging calculation, whether or not FMV comparison and analysis is required. Allowed activity on the interstate roadsides, and access to these areas, is proscribed and

2 https://www.fhwa.dot.gov/publications/publicroads/15sepoct/02.cfm

limited by U.S. law and U.S. DOT, FHWA and State DOT regulation and guidance, and is controlled by the FHWA and State DOTs.

There are multiple methods by which State DOTs can monetize solar PV in ROW areas. Most direct methods by which State DOTs can monetize ROW solar fall in five four main categories: 1) land lease or license agreements, 2) power purchase agreements, 3) direct energy sales, 4) profit share and capacity fees, and 45) renewable energy credit sales. This list is not exhaustive as these agreements are contracts whose terms can be negotiated. Broadly, diversifying transportation funding streams will stabilize State DOTs over time, helping them to become more resilient as economic and operating conditions change, and providing necessary resources for modernizing transportation infrastructure as mobility becomes autonomous, shared, electric and innovative.

Furthermore, the development of solar PV in ROW areas can create additional, significant value for State DOTs, independent of and concurrent with direct monetization methods. For example, a day one benefit of PV solar development in ROW areas would be for the responsibility for maintaining the site to be transferred to the utility or solar developer for the duration of the project, which may extend 30 years or more. States have between 440 and 6,600 acres of ROW area (depending on the state) in interchanges available for solar installation that are otherwise maintained by the DOT, typically through mowing and herbicide application. The significant savings in roadside maintenance can create resources and funding that State DOTs can deploy to other critical operations and maintenance activities.

The chart below explains the requirements for permitting a project as a utility facility and those for a project requiring a right-of-way use agreement.[3]

	State definition allows for renewable energy to be considered as a utility facility *and* the project serves the public	**State law excludes renewable energy as a utility facility, project is not serving the public, or utility elects not to apply for a utility permit**
Applicable Federal Regulation	23 CFR part 645 Accommodation of Utilities	23 CFR part 710 Right-of-Way Use Agreements
Process	A State DOT's Utility Accommodation Policy (UAP) outlines the procedures, criteria, and standards it uses to evaluate and approve individual applications for utility facilities within the ROW. The FHWA Division Office reviews and approves new and revised UAPs	State DOTs may execute a ROW use agreement for a renewable energy project. This requires a determination by FHWA that such use is in the public interest; is consistent with the continued use, operations, maintenance, and safety of the facility; and such

3 https://www.fhwa.dot.gov/environment/sustainability/energy/publications/renew_energy_row_guide/index.cfm

	for compliance with Federal requirements. The State DOT then enters into written arrangements setting forth the terms for a particular project. The State DOT can approve a utility project installation in accordance with the process outlined in the UAP without referral to FHWA.[4]	use does not impair the highway or interfere with the free and safe flow of traffic.[5] An application for a ROW use agreement approval must include planning and design details about the project, including provisions for maintenance access, terms of use, maps, plans, and sketches.[6]
FHWA Approvals Required for Renewable Energy Use of ROW	The FHWA must give programmatic approval of the UAP; project by project approval from FHWA is not required unless the proposed installation is not in accordance with 23 CFR part 645 or the UAP.[7]	FHWA approval is required for eachuse.[8] For non-Interstate projects, FHWA may assign approval authority to the State through their 23 U.S.C. 106(c) Stewardship and Oversight Agreement.[9]
FHWA Approvals Required for Access Control Changes on the Interstate	The State DOT must obtain written approval from FHWA prior to any temporary or permanent modification of access control on the Interstate System.[10]	The State DOT must obtain written approval from FHWA prior to any temporary or permanent modification of access control on the Interstate System.[11]
Approvals Required for Access Control Changes on Non-Interstate Federal-aid Highways	Approval is required prior to any temporary or permanent modification of access control on non-Interstate highways.[12] The approving authority for NHS highways is determined by the FHWA-State DOT Stewardship and Oversight	Approval is required prior to any temporary or permanent modification of access control on non-Interstate highways.[14] The approving authority for NHS highways is determined by the FHWA-State DOT Stewardship and Oversight

4 23 CFR part 645

5 Except on Interstate highways, FHWA may assign its approval responsibilities to the State DOT. 23 CFR 710.405(a).

6 23 CFR 710.405.

7 23 CFR 645.215.

8 23 CFR 710.403(b)

9 23 CFR 710.405(a).

10 23 U.S.C. 111(a), 23 CFR 710.403(a). The approval applies to segments that have received Federal-aid funds.

11 23 U.S.C. 111(a), 23 CFR 710.403(a). The approval applies to segments that have received Federal-aid funds.

12 23 CFR 620.202 and 620.203(a) and (h); see also 23 CFR 710.405 and 23 CFR 645.211. The approval applies to segments that have received Federal-aid funds.

14 23 CFR 620.202 and 620.203(a) and (h); see also 23 CFR 710.405 and 23 CFR 645.211. The approval applies to segments that have received Federal-aid funds.

	Agreement. For non-NHS highways, the State DOT is the approving authority.[13]	Agreement. For non-NHS highways, the State DOT is the approving authority.[15]
Does FHWA require the State DOT to charge a fee?	No. Fees charged for utility use, and the disposition of such fees by the State, are at a State's discretion.[16] The FHWA does, however, encourage States to use generated revenues for transportation purposes.	Yes, if Title 23 funds were used to acquire the ROW (subject to exceptions under 23 U.S.C. 156(b) and 23 CFR 710.403). Fair market rent is required for use of the ROW, unless there is an applicable exception or justification that the project is in the public interest based on social, environmental, and economic considerations, in which case an exception may be approved. The Federal share of the net income must be used for title 23-eligible purposes in accordance with 23 U.S.C. 156(c).
How does FHWA ensure the renewable energy project does not cause safety, aesthetic, or other problems?	The FHWA uses its stewardship and oversight program to make certain the State DOT meets these responsibilities.[17]	Through FHWA review and approval of the ROW use agreement.[18]

Land License/Lease Agreements

One way for State DOTs to generate revenue from ROW solar projects is to associate a fee with the land lease or license, and contract for that fee from the solar developer for the duration of the agreement. Land lease agreements grant a tenant a legal right to exclusive possession of premises for a specified period in return for the payment of rent. Land license agreements are similar, but the right to occupy the premises is not exclusive. Land lease and license values will likely vary depending on location and solar resource quality.

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[13] See 710.403(a).
[15] See 710.403(a).
[16] This exception to 23 U.S.C. 156(c) is based on conference report language for section 126 of the Federal-Aid Highway Act of 1987 (Title I of the Surface Transportation and Uniform Relocation Assistance Act of 1987, Pub. L. 100-17 (Apr. 2, 1987)). With respect to 23 U.S.C. 156 provisions on income from right-of-way, added by the Act, the report stated "[t]he charges and disposition of fees for utility use and occupancy of right-of-way will continue to be governed by 23 C.F.R. 645" (H.R. Conf. Rep. 100-27). The FHWA also has broad authority to establish utility accommodation criteria under 23 U.S.C. 109(l).
[17] 23 CFR 645.215(b).
[18] 23 CFR 710.405.

Licenses, or leases when applicable, are legally binding contracts between the land owner and the solar developer, so specific attention should be paid to the terms of the agreement, especially any recourse that the holder of the license or lease would have if the agreement were broken [6].

Because there are currently few ROW solar projects, it is difficult to estimate the per acre land lease values directly. Lease basis prices are often set at a $/acre-yr. Lease terms can also include fee escalation rates or remain flat for the duration of the lease. Land lease values vary significantly (few hundreds to thousands of dollars per acre-year) across the U.S. and would likely be influenced by how much improvement is necessary at each site and any competing land uses.

Existing lease agreements with other third-party entities may include terms that limit the use of the property for solar PV installation. In addition, tax-exempt governmental bonds have compliance requirements under the Internal Revenue Code that must be met for as long as the bond is outstanding. State DOTs should work with their internal finance and real estate divisions to understand the lease and bond status on any property that is considered for solar PV development.

Power Purchase Agreements (PPAs)

Power purchase agreements (PPAs) are contractual agreements to buy and sell energy [7]. While they are not exclusive to renewable energy projects, they are often required for renewable energy project developers to secure third party financing. Because solar PV farms are frequently located away from the party buying the power, modern PPAs are often formulated as virtual PPAs.

In a "contracts for differences" PPA model, the PPA holder (the one buying the power), still buys electricity from their local utility, but contracts for the electricity produced by the solar farm for a fixed (or escalating, depending on the contract) price. For instance, if the PPA terms indicate that the PPA holder will buy power for $25/MWh, but the wholesale market price where the solar power is produced is $35/MWh, the solar farm owner will pay the PPA holder the difference, or $10/MWh. However, if the wholesale market price where the solar power is produced is $20/MWh, the PPA holder will pay the solar farm owner the difference, or $5/MWh. Thus, it is in the financial interest of the PPA holder to negotiate a contract rate that is, on average, lower than the expected wholesale market rate at the agreed upon clearing location[19].

Alternatively, in certain deregulated capacity energy markets DOTs can enter into PPA agreements where they buy the power directly from the solar developer and pay a $/kWh of energy delivered. This price could be fixed or have an escalation rate attached, typically between one and two percent per year for the life of the contract. The PPA rate is not impacted by the larger wholesale market price of energy and often includes the full cost of the energy generation, transmission, and delivery.

In both PPA models, State DOTs could buy the power, or the solar developer might sell the power to a third party and State DOTs could receive a portion of the revenues, collect a land license/lease fee, and/or a capacity fee. In areas with good solar resources, PPA contract prices

[19] Because PPAs are contracts, price clearing locations are negotiable and could be anywhere. They could be at the exact grid node at which the solar power is injected on the grid, or at a hub (an average regional price).

for large utility-scale solar PV farms have declined to almost $20/MWh ($0.02/kWh, generation costs) [8], well below wholesale electricity costs. If State DOTs work with their utility or a solar developer to develop ROW solar projects, then it is possible to negotiate PPA rates so that State DOTs see significant savings on their utility costs. These savings would result in the flexibility to direct limited transportation resources and funding to mission critical transportation activities - simply by enhancing the use of their ROW areas.

Direct Energy Sales

In some locations, State DOTs might also be able to own the solar PV assets themselves and sell the power back to the utility. A State DOT could contract with a developer to build and operate the solar PV project for a fee, including necessary interconnection infrastructure upgrades. While the return on investment would be direct to the State DOT, available tax incentives such as the FITC cannot be leveraged by state agencies. To take advantage of the tax incentives, the State DOT could use a hybrid model where they enter a PPA agreement with a solar developer with the option to buy the system after a set amount of years of operation. How this electricity is priced will depend on the type of market that the solar project operates in. In general, DOT-owned solar arrays might be net-metered and/or meter aggregated, be given a value of solar tariff, or compensated at wholesale or retail electricity rates.

Net metering: Net metering is a simple way to compensate customers for the solar energy they produce. In a net metering scenario, solar owners only pay the utility for the net amount (electricity consumption minus solar electricity generation) of electricity that they consume. For example, if a customer used 400 kWh of electricity per month, but also generated 100 kWh per month with their solar array, they would only pay the utility for the difference, 300 kWh per month.

Meter aggregation: Meter aggregation allows multiple meters to use the energy produced by a single solar PV system through virtual net metering. State DOTs have many electric accounts and meters; however, these meters are often not located near roadside ROW properties that are prime locations for solar PV installations. If there are meters located nearby, they often don't have a high enough energy demand to consume all of the energy generated by the solar PV system. State DOTs that are interested in consuming the energy produced by the solar PV systems installed on their property benefit greatly from meter aggregation because the meters and the solar PV system do not have to be sited at the same location, and the State DOT can use multiple meters to match the energy generation of the solar PV system.

Value of solar tariff: A value of solar tariff (VOST) differs from net metering in that the VOST can be more (or less) than the cost of grid electricity. Because solar often aligns with peak demand times, the value of that production can be higher than the average price paid to the utility. Programs differ, but VOSTs are usually set by utilities and because they are based on market conditions (price of wholesale rates, transmission costs, etc.) can be updated regularly. For example, if a customer used 400 kWh of electricity per month, but also generated 100 kWh per month with their solar array, they would pay the utility for 400 kWh at the local utility rate, but would also receive a bill credit for 100 kWh at the VOST rate.

Wholesale and retail electricity rates: Depending on the market, solar customers are compensated at average or actual wholesale electricity rates or are compensated at retail electricity rates. In some markets, all generators over a certain capacity size are required to be compensated at wholesale market rates. Wholesale rates are often much lower than net-metering or VOST rates.

Revenue share and capacity fees

State DOTs can also generate revenue from siting renewable energy in their ROW by entering into revenue share agreements and and/or charging capacity fees. A revenue share agreement is when the utility or solar developer agrees to pay a certain percentage of the revenue generated by the PV system located on DOT property to the DOT.

A capacity fee is a predetermined amount of money collected by the DOT annually per MW nameplate capacity of the system located on its property. The capacity fee is normally collected once the PV system starts producing, or is scheduled to start producing, energy.

Renewable energy credits

A renewable energy credit (REC) is technically defined as a "market-based instrument that represents the property rights to the environmental, social and other non-power attributes of renewable electricity generation [9]". RECs are financial instruments that allow the purchaser the right to claim to use renewable energy even if the actual power they consume comes from different sources. For instance, a firm in Georgia could claim to be "100% renewable" by purchasing enough RECs from a solar farm in California to offset the amount of local electricity they consume even though that electricity might have been generated by a fleet of power plants that included natural gas or coal.

Solar RECs (SRECs) are created by generating electricity from solar PV systems. For every one MWh generated by a solar PV system, one SREC is also generated. These SRECs can then be sold to energy users that are looking to offset the environmental impacts of their electricity usage. For example, if an energy user consumed 200 MWh of electricity per year from the electricity grid, by purchasing 200 RECs, they can claim to consume only renewable energy, no matter the relative locations of the energy user and the solar farm.

State DOTs could negotiate to retain all or a portion of the SRECs generated by solar PV sites on ROW areas, regardless of whether the State DOT engages in a PPA. State DOTs can then monetize the SRECs at regular intervals for the life of the system. The retention of SRECs by the State DOT will impact negotiated land license fees, revenue share, or PPA rates. Since SRECs are subject to supply and demand markets, the value of SRECs can vary over the life of the solar PV system.

Sometimes SRECs are bundled with other parts of the contracts or kept separate. For example, a solar developer might sell electricity at a certain price through a PPA to one party but sell the SRECs to another party. If the PPA terms were such that one party bought both the energy and the SRECs, the buyer could then sell them to someone else if they wanted to. SREC value varies significantly by location, and their value can be volatile. Current U.S. SREC prices range between a few dollars to the few hundreds of dollars [10].

Methodology

In this analysis, the method by which solar potential was assessed for ROW areas involved dozens of data sets and multiple custom sub-process methods. The summary of each of the workflow segments for analysis is shown in Figure 1. Each sub-process will be discussed in more detail in the following sections.

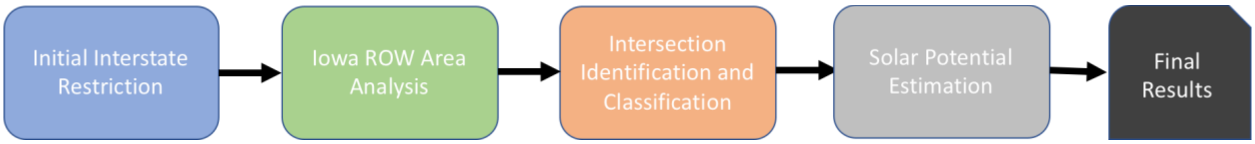

Figure 1. Summary workflow for solar potential analysis showing how the raw data were used to generate appropriate estimates of ROW solar locations and estimate energy production.

Initial Interstate Restriction

There are various limitations that restrict the interstate areas that are viable for installation of solar PV. The first step of the analysis was to reduce total length of interstate ROW under consideration by applying appropriate restrictions. Existing interstate data were provided by FHWA [11]. The lack of data accurately describing ROW areas, and the usable format of data sets, significantly limits an analysis of interstate roadsides to accommodate renewable energy infrastructure. The same challenges exist for state highways and other major roads. While interstate ROW areas were selected for this analysis, the analysis and web tool developed could certainly be applied to and expanded to state highways in the near future. The restricting criteria used to limit interstates for this study were:

- Within 5 miles of transmission lines [12]
- Outside of National Parks [13]
- Outside of National Forests [14]
- Outside of Protected Areas [15]
- Outside natural gas, HGL and crude pipelines [16] [17] [18]

Thus, for an area to be further considered for ROW solar, it had to satisfy all the above criteria. All these data served as inputs for geoprocessing in custom R [19] scripts to yield data sets of interstates viable for solar for each state, as shown in Figure *2*.

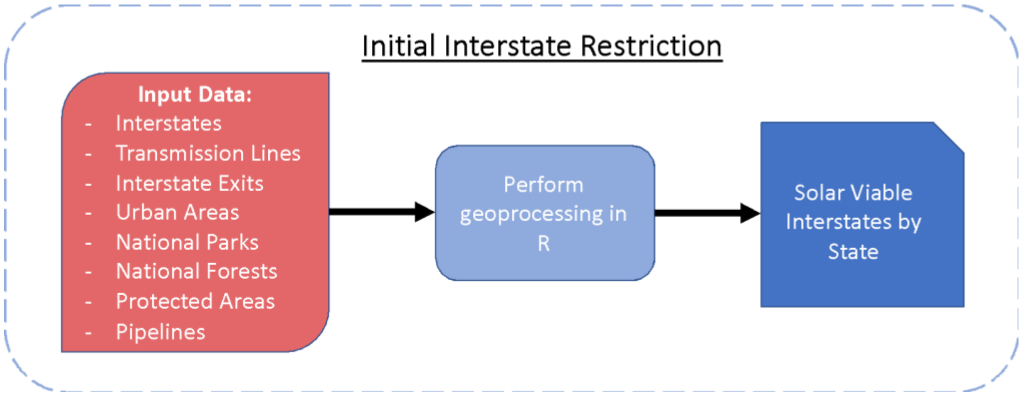

Figure 2. Initial interstate restriction sub-process diagram showing input data used for restrictions of interstate areas viable for solar development.

This analysis was performed for all 48 contiguous states; however, for brevity, the effect of these restrictions will be demonstrated using the case study of Georgia. Figure *3* shows the remaining interstates in Georgia through the progression of restriction used for analysis in this study.

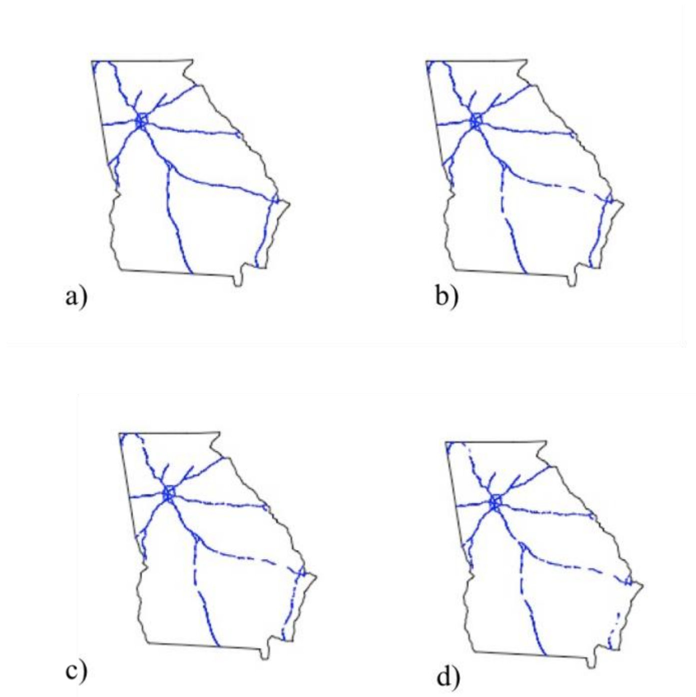

Figure 3. Series of images of Georgia showing the restriction of interstates based upon the selected criteria for a) all interstates, b) interstates within 5 miles of transmission lines, c) interstates outside National Parks, National Forests and other protected areas and d) interstates outside pipeline routes.

Interstates were restricted to within 5 miles of transmission lines to take advantage of existing electrical infrastructure and minimize project complexities, including the costs associated with the installation of new transmission lines. The distances from existing transmission lines were assumed to be reasonable distances that would not unfairly eliminate potential interstate ROW from consideration while also observing existing cost and infrastructure limitations[20].

It was assumed that ROW spaces along interstates through urban areas would be narrow in width and taken up by frontage roads and other developments, making them unavailable for solar installations. Therefore, interstates through designated urban areas were also eliminated from analysis.

Due to restrictions within these protected areas, interstates through National Parks, National Forests, and other protected areas were eliminated from analysis. The protected areas used are defined as being "dedicated to the preservation of biological diversity and to other natural (including extraction), recreation, and cultural uses, managed for these purposes through legal or other effective means [15]." These protected lands vary widely in terrestrial type and overseeing agency and include protected lands such as wetlands, areas of critical environmental concern and historic or cultural areas. Some of these lands are designated as available for multiple use, such as extraction or recreation and these lands were excluded from analysis so that interstates through these areas would still be considered.

Finally, interstates near existing pipelines were eliminated. Pipelines considered included hydrocarbon gas liquids (HGL) pipelines, natural gas (NG) pipelines, and crude oil pipelines. Generally, solar panels are not likely to be installed on land directly above underground pipelines because they could impede pipeline maintenance, so interstates within 500 m of existing pipelines were eliminated.

Not all interstates remaining after this elimination process will be suitable for solar panel installation within the ROW; however, this analysis does effectively restrict interstates for further examination to areas where solar installation is possible depending on ROW area available. These restricted interstates were used for all subsequent analysis.

Iowa ROW Area Analysis

Due to data limitations, it was not possible to complete detailed analysis of actual ROW areas available for solar in all states. During the initial data gathering step, Iowa was the only state found with accessible geographic information system (GIS) data showing the exact ROW boundaries along its interstates. As a result, extensive analysis was performed using the Iowa ROW data and those results were used to develop ROW area estimates for subsequent analyses of other states, as shown in Figure 4.

[20] Our analysis methods are flexible enough such that our assumptions could be changed if regulations were to change.

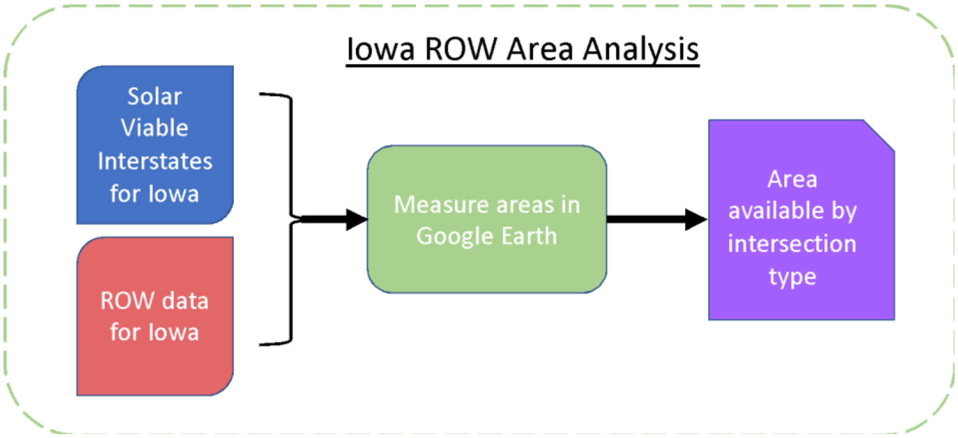

Figure 4. Iowa ROW area analysis sub-process diagram showing how the Iowa ROW data was used to approximate the average solar area available by interchange type.

Figure 5 shows an example section of interstate in Iowa with the ROW boundaries outlined in black and the interstates given in blue. The related interchange captured from Google Earth is also shown for comparison. As shown in this figure, interchanges are the most consistent locations with the greatest ROW area potentially available for solar panels. Extensive analysis of these data was performed to estimate the area available for solar installations in ROWs in Iowa and conclusions from this analysis were applied to the other states.

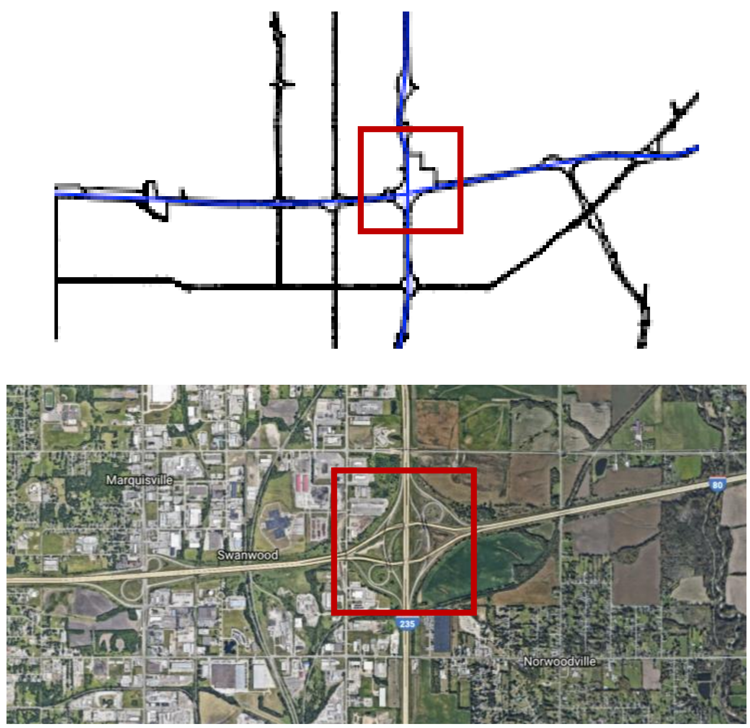

Figure 5. Example of Iowa ROW data and related Google Earth *[20]* image showing the additional ROW area associated with interstate interchanges and junctions. The red box indicates the same interchange in both images. The top part of the figure shows the ROW boundaries in black and the interstates themselves in blue.

Available ROW area for solar installation was determined considering National Highway Traffic Safety Administration (NHTSA) requirements for shoulder widths and clear runoff areas. These regulations require that each interstate lane be at least 12 feet wide with a 10-foot shoulder. The required width of the clear zone outside of the shoulder varies based on interstate speed and terrain but for this analysis it was assumed to be 40 feet. Visual analysis of existing solar fields led to a minimum width requirement for solar installation of 30 feet (a single row of PV panels). Based on these width requirements and analysis of the available ROW data, straight sections of interstates are often not wide enough for solar installations. Locations of interest with available ROW area are generally found at rest areas and within the interchanges with other major roads. These interchanges are typically found to resemble one of two shapes: either diamond or butterfly. Examples of these interchanges are shown in Figure 6 and Figure 7 respectively with the ROW outline designated by the white lines (the ROW data from Iowa DOT) and the available area for solar installations outlined in red (our analysis). An example rest area is shown in Figure 8. All images were taken in Google Earth using ROW data provided for the state of Iowa.

Figure 6. Example diamond interchange showing expected area for solar PV installation outlined in red

Figure 7. Example butterfly interchange showing expected area for solar PV installation outlined in red

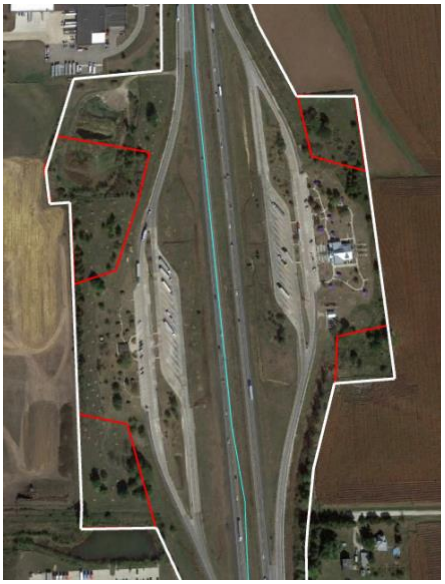

Figure 8. Example rest area showing potential area for solar PV installations outlined in red

Most of the area (~67%) with potential for solar in Iowa ROWs was found to be in rest areas or in other tracts of land owned by the State DOT, but not within interchanges. However, without specific data detailing the extent of area along interstates controlled by the State DOT, there is no visual, or otherwise, means to identify such areas in other states. *As a result, for all other state's without sufficient ROW data available, further analysis was performed only for interchanges because they are visually identifiable along interstates.* A more detailed and accurate assessment of ROW area available for solar would require complete ROW data for each state.

Interchange Identification and Classification

Based on the Iowa ROW results which showed that only interchanges and rest areas are viable for solar installations and a lack of ROW data for other states that outlines ROW boundaries at rest areas, *further analysis was done assuming that only the interchanges that fall within the bounds of the restricted interstates were viable for solar*. To estimate the amount of area available for solar in each interchange, a sample of 50 interchanges of each type (diamond and butterfly) were randomly selected from across the U.S., with at least one interchange from each of the states considered in the sample. Using this sample, an average total butterfly interchange area of 33.1 acres and average total diamond interchange area of 11.7 acres was calculated. Further information about this process can be found in Appendix A.

However, due to safety restrictions, solar panels cannot be installed within the entire area of each interchange. Appropriate space must be left to meet clear zone and other regulations. A schematic for an existing interchange in Georgia that has already been appropriately sited for solar was provided by The Ray and was used to estimate the fraction of total interchange area that would be viable for solar. This fraction was found to be about 41%. Further information about the calculation of this fraction can be found in Appendix A. Knowing the expected area available for solar in each interchange type was crucial for estimating the amount of solar potential in each state based upon the number of each type of interchange of interest within that state.

Using the restricted interstate files for all states and another data set which marks the locations of interstate exits, locations of interchanges were determined, and images of these interchanges were captured. These interchanges included diamond and butterfly interchanges of interest as well as 'other' interchanges that might have some space available for solar but do not fit into either of the two interchange patterns identified. Once all these images were captured, they were categorized and counted via a human-in-the-loop classification technique. In addition, visual inspection of these interchanges removed false positives that were captured by the algorithm. Figure 9 shows the entire sub-process.

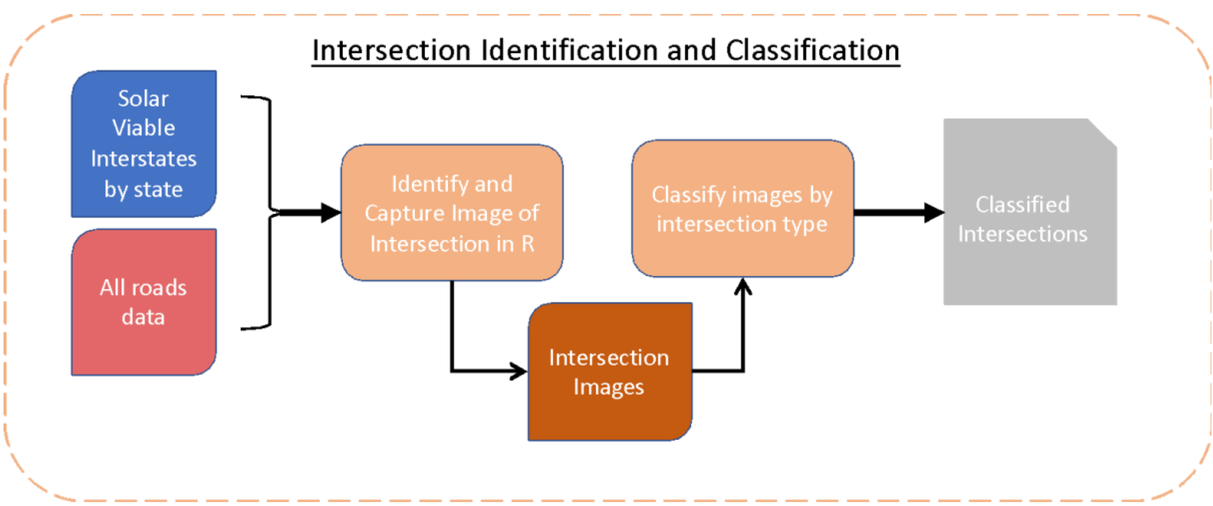

Figure 9. Interchange identification and classification sub-process diagram showing how images of interchanges in each interstate were captured and then classified for further analysis.

- Identify and capture image of interchange in R

It was assumed that all interchanges were co-located with exits along interstates, so the solar viable interstates and exits data set were used together to identify all exits that fall along lengths of the solar viable interstates. At the location of each exit of interest, an image was captured that would allow for subsequent classification of images by interchange type.

- Classify images by interchange type

Due to the variability of images captured, even for the same interchange type, human-centered classification was deemed to be the most accurate and effective way of classifying the interchanges captured. A script was written in R to aid in the classification which subsequently displayed each image and took a human input for one of the four programmed interchange types (butterfly, diamond, other and none). Example images used for classification are shown in Figure 10. The code then saved the designated interchange type and coordinates of the interchange for each image in a separate file aggregated by state. The classified interchange results could then be used for analysis of solar potential in each state.

- Remove duplicate interchanges

The way the exit data were structured, each interchange was paired with two exit points. In order to remove this duplication of interchanges, after interchange classification (so that all false interchanges had already been removed from analysis), duplicate interchanges were removed based upon distance between interchange points. The threshold for duplication was set at 1 km (0.62 miles), essentially assuming that exits located on the same interchange would be within 1 km or less of the duplicate point and that exits located more than 1 km from another exit would be on a different interchange. In order to further eliminate duplicate interchanges that weren't captured by this algorithm, a manual inspection of all remaining interchanges was performed, and duplicates were identified and removed.

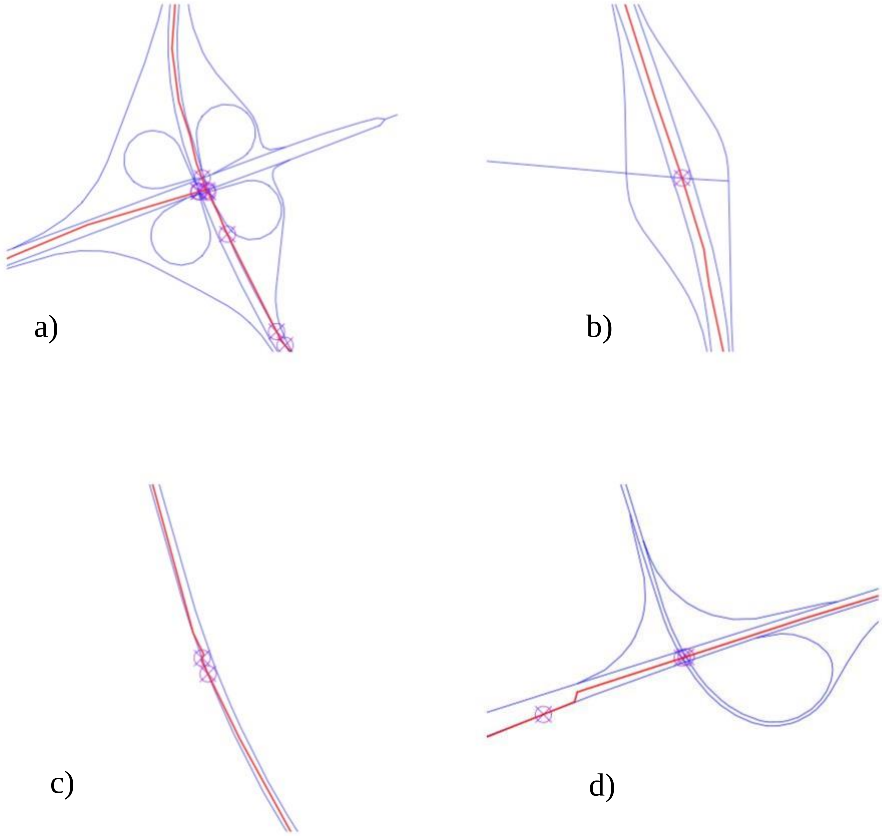

Figure 10. Interchange images showing examples of a) butterfly interchange, b) diamond interchange, c) faux interchange, and d) other interchange used for classification. Red lines indicate the solar viable interstates from previous analysis and blue lines are data from all-roads. Purple hatch circles are interchanges identified by the computer.

Method limitations

One major limitation of this method is the restriction of solar areas to only interchanges, which is not representative of all potential area in the ROW. Areas not included in the current analysis and web tool include rest areas and other large tracts of ROW land. For Iowa, the total area available for solar in ROWs based upon analysis of actual ROW data is approximately 1,200 acres. Based upon the interchange classification method, Iowa has approximately 400 acres available in interchanges for solar. This means that only about 1/3 of the available ROW area was captured by the interchange classification method. However, until detailed ROW data are available for other states, the interchange classification method provides a useful, if not conservative, means of approximating available area as well as identifying the location of interchanges of interest for possible solar development.

Solar Potential Estimation

Once all interchanges were appropriately classified for each state, the corresponding area and solar capacity factor could be assigned to each interchange based on its classification and location [11]. Total area available for butterfly and diamond interchanges used in analysis was 33.1 acres and 11.7 acres respectively, as discussed in Section interchange Identification and Classification. Interchanges classified as ‘other’ were assumed to have an available area of 22.1 acres. For all interchange types, 41% of total area was deemed viable for solar, based upon analysis of The Ray interchange schematic discussed in Appendix A. This value was used as the solar development factor for analysis.

These results were used to estimate the solar potential at each location, as shown in Equation 1. According to previous solar ROW projects, approximately 0.43 MW can be installed per acre of available land. This value was used as the solar area factor for analysis. Using state specific average commercial electricity prices for all sectors [13], the monetary value of the solar available at each site was estimated using Equation 2. This process is further explained in Appendix B.

$$solar\ potential\ \left[\frac{MWh}{yr}\right] = area\ [acres] \times solar\ area\ factor\ \left[\frac{MW}{acre}\right] \times capacity\ factor \times 8760\ \left[\frac{hrs}{yr}\right] \quad (1)$$

$$electricity\ value = solar\ potential\ \left[\frac{MWh}{yr}\right] \times commercial\ electricity\ price\ \left[\frac{\$}{MWh}\right] \quad (2)$$

Results

Detailed results for each interchange analyzed, including coordinates, state, county, estimated annual solar potential [MWh/yr], and estimated annual electricity value [$/yr], are provided in the included spreadsheet Ray Solar Interchanges Results. This spreadsheet allows for users to change key input parameters including the solar development factor, solar area factor, area associated with each interchange, and electricity price. These results are presented visually in the web tool, which also allows for users to change inputs of interest. Figure 11 and Figure 12 show state aggregations of the potential energy production and energy value, respectfully.

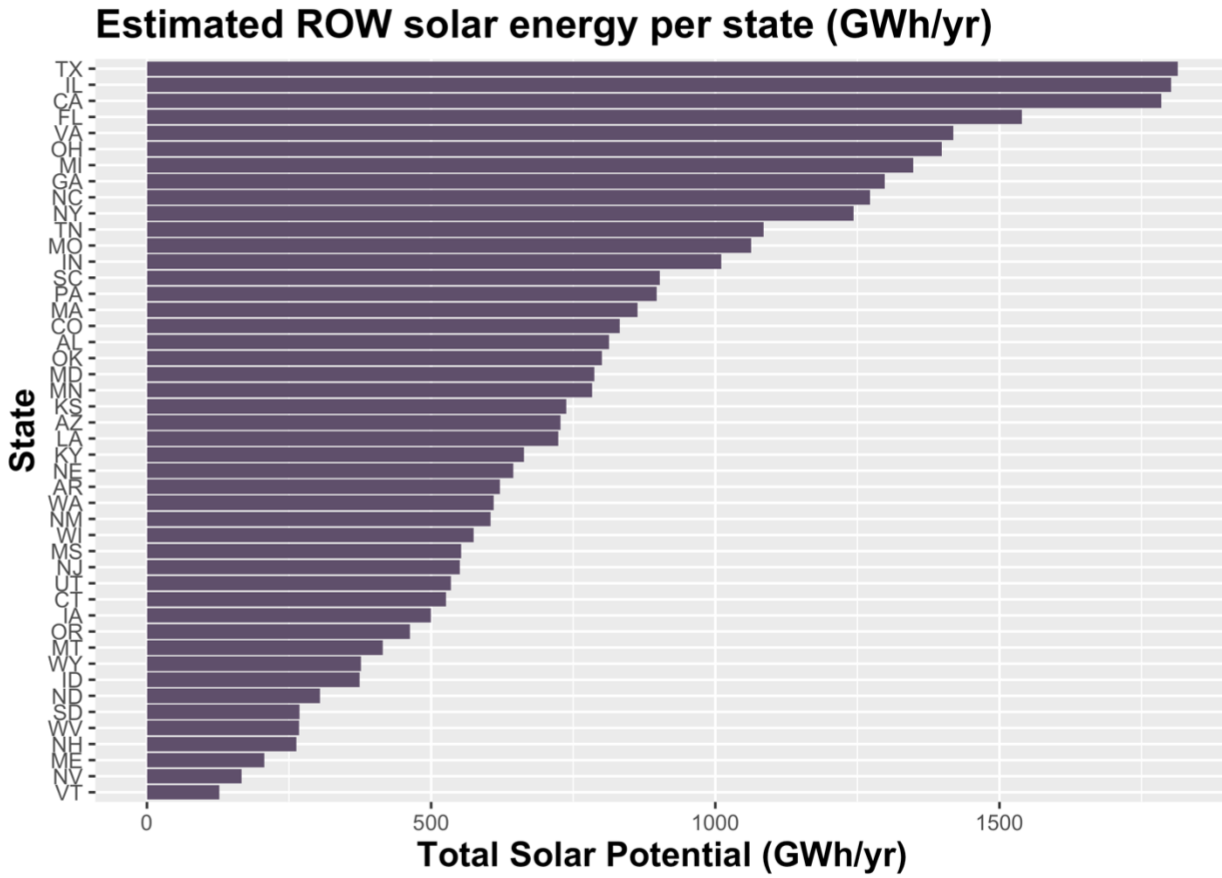

Figure 11: Figure showing the potential solar energy (GWh/yr) per year if every identified interchange in each state were developed with solar. Note the Delaware and Rhode Island are omitted from this figure for lack of available interchanges to develop.

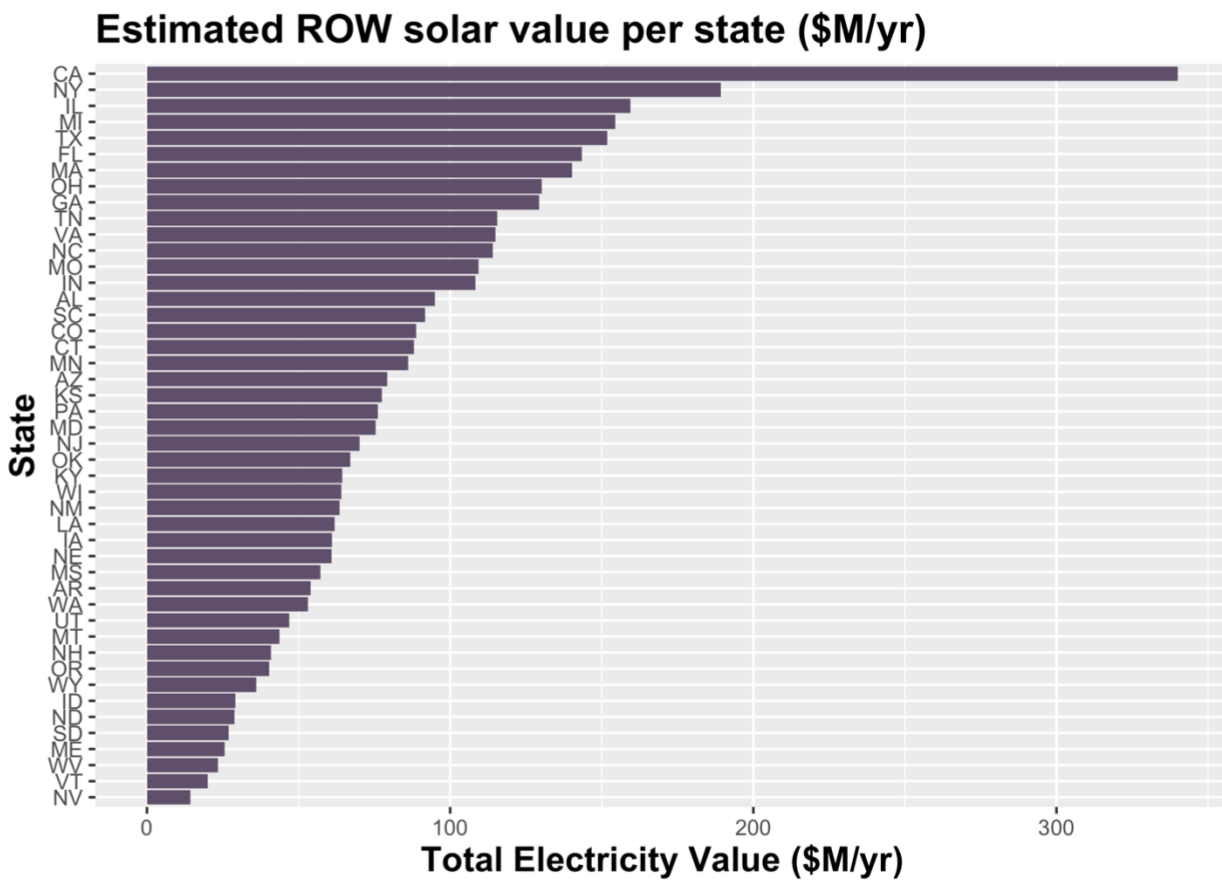

Figure 12: Figure showing the potential solar energy value ($M/yr) per year if every identified interchange in each state were developed with solar. Note the Delaware and Rhode Island are omitted from this figure for lack of available interchanges to develop.

Note that the order of states varies between the figures as states have considerable variability in electricity prices. For instance, California has the third overall potential to produce energy in its interstate interchanges, but because of higher average electricity prices, provides almost twice the value of the next closest state, New York.

Web tool

The results of analysis were extended into a web tool that allows for policy makers to easily assess the results on an interactive spatial scale. The web tool can be found here:

https://utw10982.utweb.utexas.edu/

The web tool shows the location, size, estimated solar energy production, and estimated value of that solar production for every state in the contiguous 48 states in the United States. The results of this analysis provided the default assumptions and estimates for the web tool, but the tool allows users to change some of the underlying assumptions, such as 1) the solar capacity factor (to analyze future technology improvements), 2) state electricity rates (to assess projects under changing economic factors), and 3) area available for solar (to simulate policy changes that allow for more solar deployment in ROWs).

Conclusions

This analysis considered the potential for installation of solar PV in ROWs along interstates in the contiguous 48 US states. Based upon analysis of existing ROW data, long narrow stretches of ROW along interstates (the vast majority of ROW land) are generally too narrow to allow for installation of solar PV while meeting all existing safety and other regulations governing ROW use and development. Therefore, the best potential areas are interchanges and rest areas along interstates.

Existing interstates were restricted based upon various criteria deemed appropriate for solar development. Based on these restrictions, most states still have significant lengths of interstate with potential for solar development. Interchanges within these restricted interstate lengths were identified and evaluated to estimate the potential solar capacity and related electricity value that could be installed. The results from this analysis, including location of such interchanges and estimated solar potential, are provided in the web tool and related documentation.

The findings of this analysis demonstrate that there is significant potential for electricity production by installing solar PV projects in interstate interchanges of the ROW within the U.S. However, federal law and some FHWA regulations limit renewable energy infrastructure development in ROW areas. For example, currently FHWA will not allow development in ROW areas that lack “secondary access,” which is site access other than the interstate lanes themselves. The impact of the secondary access limitation is to eliminate usable and appropriate acreage at some interchanges, including many that have a butterfly or cloverleaf configuration, from solar PV project planning and execution. The modernization of existing federal law and regulations could open significant ROW areas for solar PV development.

Additionally, states considering ROW solar projects should first develop full spatial ROW data sets that can be used to find the most appropriate locations for solar PV, and identify other locations with large tracts of unused ROW land that weren’t identifiable by the interchange analysis done for this project.

Future Work

Due to a lack of available data on ROW boundaries in states, current results are based only on installation of solar PV in existing interchanges. However, the analysis of Iowa ROW data showed that the majority (~67%) of available ROW area was found near rest areas or other large tracts of land that are not included in this analysis. As ROW data that include detailed boundaries are developed for each state, further analysis, like that used for the case study of Iowa in this project, could refine local results. Detailed ROW data would allow for inclusion of non-interchange areas to be considered for solar assessment and development. Additionally, the current analysis could be extended to Alaska and Hawaii.

Additionally, current results use an approximate area value for each interchange type and not the actual area. For future development of these sites, measured areas at each interchange would provide more accurate results and estimations of solar potential[21]. The associated web tool allows for users to change the area at each interchange and see the updated potential.

Acknowledgements

The authors would like to thank The Ray C. Anderson Foundation and The Ray project for supporting this project. The authors would also like to thank Allie Kelly, Laura Rogers, and Harriet Langford for their intellectual input and support throughout the development of this report, related data products, and web tool.

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[21] Specific area measurement and analysis has been done for five interchanges [Exits 2, 6, 13, 14, and 18] along I-85 in Georgia and these results are included in the spreadsheet and web tool

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Appendix A

Analysis of The Ray Interchange for Estimation of Solar Area

To estimate the potential area available for solar in each interchange type, two pieces of information were needed:

1) The average total interchange area for each interchange type
2) Fraction of total interchange area that could be developed with solar

Average total interchange area for each interchange type

The shape and size of interchanges of similar type (i.e., butterfly and diamond) vary widely across the country. For the purposes of this project, an average total interchange area for each interchange type was used to estimate the area available for solar in each interchange. To capture the variations in interchanges across the country, a random sample of 50 interchanges of each type were selected, with at least one interchange of that type selected from each state. Geospatial analysis tools were used to measure the total interchange area for each selected interchange. The average of these areas was used in analysis as the estimation of total interchange area for each interchange type.

Fraction of total interchange area for solar

Due to safety-based restrictions (shoulder and clear zones) and other regulations, any development, including solar panels, are only allowed in part of the interchange area. As a result, only a portion of the total interchange area would be feasible for solar installation to include safety-based set-back requirements for the installation.

A schematic diagram of a right-of-way solar interchange developed by The Ray in Georgia was used to estimate the fraction of total interchange area that could be developed for solar. This interchange was selected because the schematic clearly shows the area that has been approved for solar, taking into account all required setbacks and other safety and regulatory requirements. The schematic can be found in Figure 1.

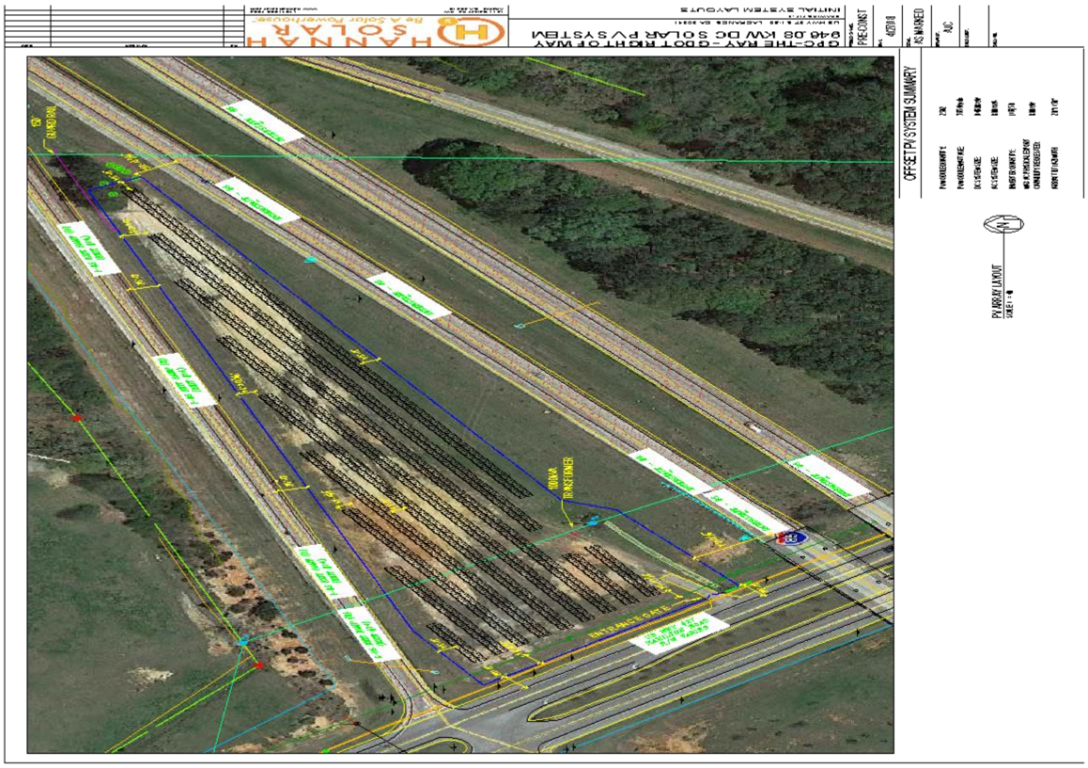

Figure 13. Schematic of interchange developed for solar by The Ray with solar panel locations indicated. Schematic provided by The Ray.

Geospatial analysis software was used to accurately measure the total interchange area and the area with solar panels visible in the schematic. The schematic was georeferenced using the coordinates of the interchange corners and a preloaded base map available in the GIS software was used to validate the correct location and georeferencing of the schematic, as shown in Figure 14. The total area of this portion of the interchange is 5.421 acres.

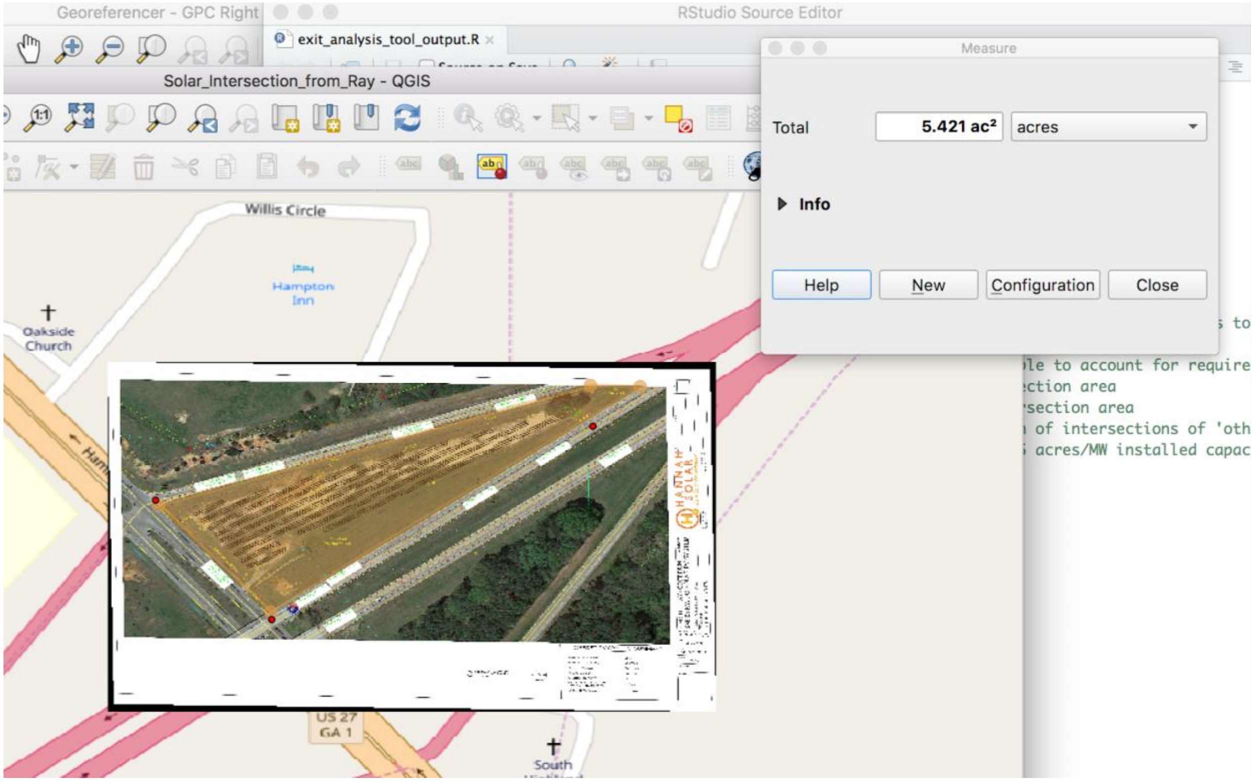

Figure 14. Measured total interchange area in GIS software. The base map in the background behind the schematic is used to verify that the schematic was properly georeferenced to the correct location to validate the area measurement. Schematic provided by The Ray.

The same georeferenced schematic and geospatial software tools were used to measure the area taken up by solar panels within the interchange. The area taken up by solar panels in this interchange is 2.197 acres, as shown in Figure 15. Using these two areas, the fraction of total interchange area that could be developed with solar was calculated, as shown in Eq. A1.

$$Fraction\ of\ total\ interchange\ area\ for\ solar = \frac{area\ taken\ up\ by\ solar\ panels}{total\ interchange\ area} = 0.41 \quad (A1)$$

z

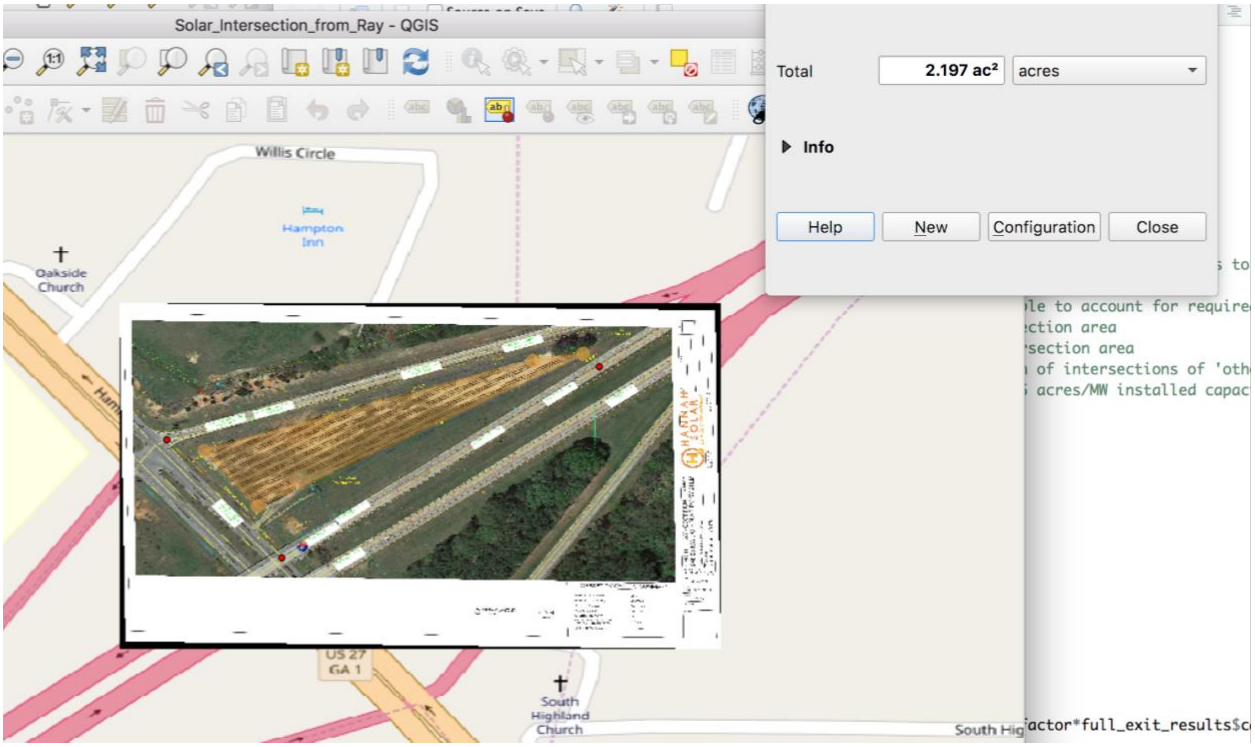

Figure 15. Measured solar panel area in GIS software. The base map in the background behind the schematic is used to verify that the schematic was properly georeferenced to the correct location to validate the area measurement. Schematic provided by The Ray.

The calculated fraction of total interchange land available for solar (0.41) was used to estimate the area available for solar for all analysis post identification of viable interchanges. This fraction accurately captures the important safety and regulatory considerations that prevent the total interchange area from being developed with solar.

This fraction was then applied to the estimated entire interchange area (21.7 acres) and thus we estimate that it would be technologically possible to build 8.9 acres (3.8 MW$_{DC}$)[22] of solar over this entire interchange. This same methodology was then applied to all the other interchanges identified by this analysis.

[22] The schematic used in Figures 14 and 15 indicated that the area chosen would accommodate 946 kW$_{DC}$ (800 kW$_{AC}$) of solar power.

Appendix B

Solar Value Used in Web Tool

There are a variety of different pathways available for the DOT to receive a financial benefit from the installation of solar PV in the ROWs of interstates (see DOT Solar Revenue Pathways section in the main report). A simple analysis of one of these pathways was performed to provide users of the web tool with an estimation of the financial value of the solar potential at each interchange examined.

For the web tool, the estimated solar value is determined assuming a net-metering scenario where all of the solar energy produced is sold back to the grid at the commercial rate. The commercial rate used for the calculation is from August 2019 [the most recent EIA data available as of December 2019] and is specific to each state. In some locations, the value placed on the solar produced might be closer to the lower wholesale electricity market price. However, data on these rates is not available for all locations, so the commercial rate is used as an approximation. The presented solar value is also different from a value of solar tariff (VOST), which might include other values such as distribution and environmental benefits. The equation used to calculate the financial value of solar potential [solar value] is given in Equation A2.

$$Solar\ value\ = solar\ potential\ \left[\frac{MWh}{yr}\right] *\ commercial\ electricity\ price\ \left[\frac{\$}{MWh}\right] \quad \text{(A2)}$$

The financial value of solar potential presented in the web tool is not meant to be taken as the direct monetary benefit that DOTs could gain from installing solar PV in the examined interchanges. Rather, it provides a consistent proxy value for DOTs and other users of the web tool to see the potential for solar PV installed in these areas and specifically as a means of comparing installations at different interchanges and amongst different states based on various state-specific characteristics, such as solar resource potential (capacity factor) and electricity prices.