Disentangling Labor Supply and Demand Shifts Using Spatial Wage Dispersion: The Case of Oil Price Shocks*

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Abstract

We separate changes in labor supply and demand through changes in higher-order moments of the wage distribution. We illustrate this idea in a study of the effects of oil price shocks, which generate a predictable labor demand adjustment across regions. Empirically, oil price shocks decrease average wages, particularly skilled wages, and increase wage dispersion, particularly unskilled wage dispersion. In a model with spatial energy intensity differences and nontradables, labor demand shifts, while explaining the response of average wages to oil price shocks, have counterfactual implications for the response of wage dispersion. Only shifts in labor supply can explain this latter fact.

KEYWORDS: Wage dispersion; Labor reallocation; Skill heterogeneity; Oil prices
JEL CODES: E24, J24, J31, J61

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1 Introduction

Why are similar workers paid differently? This is a central question in the study of labor markets. The answer to why similar workers are paid differently, of course, must be differences in labor supply or demand. Yet it is difficult to disentangle the relative importance of these two factors because of the ability of workers to relocate. When workers can migrate, changes in labor demand can induce changes in labor supply. In the end, it becomes difficult to draw sharp predictions that can be tested empirically based on first moments of wages and employment alone that will differentiate between these two channels. But it is important to know how much of labor market differences represents an optimal labor supply response of workers and what determines that response. So what can be done? In this paper, we propose a novel identification strategy that distinguishes labor supply from demand movements using changes in wage dispersion. In this paper, we pursue this strategy in the context of one particular shock that has large direct consequences for the demand for labor – oil prices.

We propose a spatial model featuring technological differences in energy intensity across regions[1] and endogenous labor reallocation between these regions. Three features of our model are central to analyze the labor demand and supply responses to oil price shocks: regional differences in energy intensity, an energy-skill complementarity as empirically estimated by Polgreen and Silos (2009), and spatial labor reallocation. When an oil price shock hits, labor demand falls asymmetrically across regions. It falls more in regions where production relies heavily on energy (say steel production in Pittsburgh) than in those that do not (say food processing in Philadelphia). The drop in labor demand is not only uneven across regions, but also across skill groups. Due to the energy-skill complementarity, the second key feature in our model, demand for skilled labor falls more than demand for unskilled labor. Our assumption of a technological energy-skill complementarity is founded in empirical evidence by Polgreen and Silos (2009) in order to explain the empirical observation that the skill premium falls after an oil price shock.[2]

Due to the asymmetric response of labor demand across regions and skill groups, wage prospects, particularly those for skilled workers, initially diverge, all else being equal. If there are different wage prospects across regions, workers have an incentive to reallocate[3] to high-wage regions. This spatial labor reallocation is the third key factor in our model. The degree of reallocation is determined by the prices of both tradeable consumption goods and non-tradeable goods such as housing or local services, which have to be purchased in the same region in which they reside and work. As Table 1 shows, expenditures on local goods make up almost half of the consumption basket of a

[1]We will use the word "region" but really we mean some geographic unit that can be thought of as a distinct labor market. In our empirical implementation, we will use the county as our unit.

[2]The argument is that skills require energy-powered machinery to be productive. Hence, productivity and wages of skilled workers co-move with the user cost of capital, a large portion of which are energy costs.

[3]In line with the applied microeconomics literature we understand labor reallocation in a broadly defined sense as pure reallocation as well as entry and exit into the labor force.

typical urban consumer. When workers decide where to supply their labor, they trade off local wages against local living costs.

Given the different wage prospects skilled workers in particular have an incentive to relocate, and they will increasingly concentrate in regions where firms operate energy-efficient technologies and pay higher wages. The concentration of labor in high-wage regions, however, drives up local living costs such as housing rent and non-tradeable services, while the opposite is true in out-migrating regions. This means that particularly unskilled workers that would have considered relocating to a high-wage region may actually decide to stay in a low-wage region because they profit from lower living expenses. Unskilled workers are more likely to stay, while skilled workers, because they are more strongly affected by an oil price shock in the first place, tend to be more mobile. As a consequence, changes in the relative supply of skilled labor mostly undoes the effect of the asymmetric labor demand response, so that skilled wage dispersion, in the end, is more or less unchanged. Because unskilled workers relocate very little, increases in the spread of unskilled wages remain. The unskilled are then compensated for an adverse shift in wages by a favorable shift in living costs.[4]

The important point of comparison is to a model with a fixed supply of labor of the two types across space. We show that the predictions for first moments such as the skill premium are the same while the effect of oil price shocks on dispersion are completely reversed. Unskilled wage dispersion does *not* change and skilled wage dispersion is affected. These differences provide a clear separation of a model that takes the supply of labor as fixed and one where worker choices determine the supply of labor. To summarize, in our model with flexible labor supply, the adjustment to an oil price shock among skilled workers is mitigated through reallocation, while changes in local prices are central for unskilled workers.

The effect of oil prices on wage levels is well-known, but, to our knowledge, this is the first paper that analyzes the response of higher moments of wages to oil price shocks and the related implications for labor allocation and local living costs. With our model, we can motivate using higher-order moments in the wage and employment distribution to distinguish between supply and demand movements. Our model has two main implications that we test empirically: when oil prices rise, unskilled wage dispersion rises and skilled wage dispersion increases only moderately compared to unskilled wage dispersion; the converse is true about the dispersion of skilled and unskilled employment. We use confidential establishment-level data from the Annual Survey of Manufactures to document these facts. Employing the method suggested by Kilian (2009) to disentangle endogenous and exogenous movements in the oil price, we find that cross-sectional dispersion of wages, mainly for unskilled workers, increases significantly in the wake of an oil price shock. For example, a one standard deviation negative shock to the supply of oil increases the

[4]Note that the model implies that we should see much less of a change in dispersion if we had access to local price indexes. This is exactly the case as shown in Moretti (2013) though the focus there is on wage inequality between high and low skilled workers.

standard deviation of wages by around 15% of the standard deviation on impact. If we turn to hourly wages of unskilled workers, the effect is approximately the same in terms of the effect of a standard deviation supply shock on between county dispersion. For skilled workers, there is no effect at all.

Our paper relates to the wide body of research on the effects of oil price shocks. Macroeconomists have traditionally focused on the impact of oil prices on the standard macro aggregates such as output, investment or inflation[5] The novel approach of our paper is to pay close attention to the higher-order moments, in particular, of wages. The paper closest to ours in its attention to labor markets is Polgreen and Silos (2009). They find that the skill premium falls after an oil price shock. In their model, a skill-energy complementarity results in a relative labor demand curve that favors unskilled labor when oil prices rise. We nest their model in our set-up and show that this mechanism – although it can explain the *level* response of skilled relative to unskilled wages – has counterfactual implications for the *dispersion* response of skilled and unskilled wages. We show that only a combination of labor demand and labor supply changes can explain both the response of wage levels and wage dispersion.

Wage dispersion may arise for a variety of reasons and the labor economics literature has studied this heterogeneity a lot. Our paper is also part of a revival in the literature that highlights the role of reallocation for aggregate fluctuations. In those models, because labor reallocation is hampered by frictions, firm-specific or sector-specific shocks lead to wage dispersion in equilibrium and fluctuations in output as workers can only be slowly reallocated. Our model is analogous to that because an oil price shock transmits differently through firms. The reallocation literature goes back to Lilien (1982); Davis and Haltiwanger (1999) and has been reinvigorated in Garin, Pries and Sims (2011): sectoral shocks lead to wage dispersion and unemployment. This result arises because sectoral labor reallocation is obstructed by frictions. A series of recent papers have formalized this idea: In Shimer (2007), search frictions delay reallocation between sectors. Wasmer and Zenou (2006) show that spatial reallocation of labor as it happens in our model is hampered by frictions. The recent uncertainty shock literature emphasises the need for real or financial frictions to explain how higher dispersion leads to a reallocation slowdown and thus to a recession (Bloom (2009); Bloom et al. (2012); Arellano, Bai and Kehoe (2010); Christiano, Trabandt and Walentin (2010); **?**). Kambourov and Manovskii (2009*a*,*b*) find that occupation-specific skills are sufficiently large to act as a friction lowering the extent of job-to-job transitions.[6]

[5]See Hamilton (1983), Kim and Loungani (1992), Kilian (2008) on output, Kilian and Park (2011) on the stock market, Kilian and Vigfusson (2011, forthcoming) on non-linearities over the cycle and Edelstein and Kilian (2009) on consumer expenditures.

[6]Labor market frictions have been also linked to oil price shocks in Loungani (1986). One may also think about oil price shocks being relevant for commuting decisions. Rupert, Stancanelli and Wasmer (2009) find that this does matter, but only for low-income groups where gasoline makes up a large share of total expenditures.

2 Empirical Evidence from the Annual Survey of Manufactures

- `set up as combo of DH and PS`
- `describe empirical approach`
- `describe Census and oil data`
- `shock firm-level response`
- `show geographic differences (B-W county dispersion)`
- `show geographic regressions`
- `(show skilled reallocation from emery-intensive to energy-unintensive regions while unskilled generally stay)`
- `(show housing price dispersion between counties increases after oil shocks/reallocation)`

Our main empirical analysis uses confidential data from the Annual Survey of Manufactures (ASM). The other obvious source for information on wages would be the CPS. The drawback of that source, however, is the fact that there is no geographic information at a level below the state.[7] We find this geographic unit less than ideal for our model which features inter-region migration that is not very strong between states (Molloy, Smith and Wozniak (2011); Frey (2009)). Hence, we turn to the ASM, which allows us to conduct the analysis at an arbitrary level of geographic detail down to the ZIP code (subject to disclosure restrictions). For our purposes, we will take the county as the relevant unit of analysis which maps reasonably well into what we call a region in our model. The obvious drawback to the ASM is the fact that it only covers the manufacturing sector, a relatively small share of the overall economy. Yet, manufacturing is a sector where oil price shocks are most likely to have a significant impact.[8] Note that the ASM has the advantage of going back to 1972 which covers the very large oil price shocks of the 1970s and 1980s. Finally, it is important to point out that this is an unbalanced panel of establishments and we make no attempt to correct for possible attrition bias. Consistent with the model we only look at establishments that scale back employment rather than shutting down altogether.

In the Annual Survey of Manufactures, the Census Bureau collects information on annual inputs and outputs of about sixty thousand establishments. The detailed information about sampling and construction of all variables can be found in Appendix B.1. This sample accounts for a large share

[7] The CPS was never intended to be representative at such a fine level of geographic disaggregation.

[8] We also repeated our analysis using data from the CPS with its wider coverage in terms of sectors and years. While the overall results are similar in nature, the wage dispersion between states – the finest geographic level in the CPS – is much less important than that between counties. Also, the majority of migration occurs within the state (see for example Molloy, Smith and Wozniak (2011); Frey (2009)).

of employment and output in the manufacturing sector. We use the data on labor compensation, employment, hours worked, fuels and output. These are the most accurately measured variables in this sample, so we are confident that our results are robust to measurement error. The previous literature studied the impact of oil price shocks unskilled and unskilled labour and our model follows that distinction. We map skilled labour into non-production workers and unskilled labour into production workers. Wages are constructed taking the compensation of workers by skill category and dividing by the number of employees. For unskilled workers we can also compute the hourly wage as Census collects the production hours worked. Below, we will also examine how an establishment's energy intensity shapes the effect of oil price shocks on wages. We define energy intensity as the share of real fuel expenditures[9] in real output.

2.1 Measures of Wage Dispersion and Oil Price Shocks

For the purposes of our analysis, we decompose the overall wage dispersion in the manufacturing sector into wage dispersion between counties and the average wage dispersion within a county:

$$
\begin{aligned}
\sigma &= \underbrace{\sum_n \omega_n (x_n - \overline{x})^2}_{\sigma \text{ overall}} \\
&= \underbrace{\sum_j \omega_j (x_j - \overline{x})^2}_{\sigma^B \text{ between county}} + \underbrace{\sum_j \omega_j \underbrace{\sum_n^{N_j} \tilde{\omega}_{jn} (x_{jn} - \overline{x}_j)^2}_{\sigma_j^W \text{ within county } j}}_{\sigma^W \text{ average within county}}
\end{aligned}
\tag{1}
$$

[9] We could have chosen overall energy expenditures which we fear would not accurately reflect how an establishment is exposed to oil price shocks because it might substitute away to other energy sources. Fuels consist to a large extent of oil use.

Here is a decomposition that accounts for industry differences

$$
\begin{aligned}
\sigma &= \underbrace{\sum_n \omega_n (x_n - \overline{x})^2}_{\sigma \text{ overall}} \\
&= \underbrace{\sum_k \omega_k (x_k - \overline{x})^2}_{\sigma^B \text{ between industry}} + \underbrace{\sum_k \omega_k \underbrace{\sum_{n \in k} \omega_{kn} (x_{kn} - \overline{x}_k)^2}_{\sigma_k^W \text{ within industry } k}}_{\sigma^W \text{ average within industry}} \qquad (2) \\
&= \underbrace{\sum_k \omega_k (x_k - \overline{x})^2}_{\text{between industry}} + \underbrace{\sum_k \omega_k \sum_{j \in k} \omega_{jk} (\overline{x}_{jk} - \overline{x}_k)^2}_{\sigma^B \text{ average within-industry between-county}} + \underbrace{\sum_k \omega_k \sum_{n \in j} \omega_{jk} \sum_{n \in j,k} \omega_{jkn} (x_{jkn} - \overline{x}_{jk})^2}_{\sigma^W \text{ average within-industry within-county}} \qquad (3)
\end{aligned}
$$

where j denotes the county in which establishment n is located, N_j are the number of establishment in county j and $\tilde{\omega}_{jn} = \omega_n/\omega_j$ denotes the weight of establishment n within the county. In principle, one could decompose that along any arbitrary level of geographic aggregation, but we prefer the county as the unit of analysis over the state because most job-related migration occurs between counties. In the following, we limit our attention to the between-county dispersion σ^B. Of course, we do not neglect that wages are dispersed within a county as well, but in this paper we solely focus on explaining the interregional portion of wage dispersion rather than wage dispersion altogether. As Table 3 shows the between-county portion still represents a considerable share (up to a third) of overall wage dispersion. In addition to between-county wage dispersion (Figure 1), we are also interested in between-county dispersion of energy intensity as measured by the share of fuel expenditures in output (Figure 2) because our model makes predictions about this statistic as well. As Table 3 shows, between-county dispersion in energy intensity is almost half of the overall dispersion. and though the share of fuels in output may be small, it is quite dispersed.

We want to analyse the impact of an exogenous unanticipated oil price shock. We are concerned about the potential endogeneity of oil prices (e.g. Kilian (2009); **?**) in that there might be some third variable driving both dispersion and the oil price. Hence in our empirical exercise, we employ an "exogenous" measure of oil price shock. The most obvious third variable is output itself, which may directly affect wage dispersion and – because U.S. manufacturing might be large – also oil prices. Furthermore, speculation in energy markets that is orthogonal to economic activity might drive oil prices. How can one extract the exogenous part of oil price movements? Hamilton (2003) proposes measures of oil prices that reflect "structural breaks", Hoover and Perez (1994) develop a binary indicator of political events that causes oil price hikes. Finally, Kilian (2009) decomposes oil price movements into (1) exogenous oil supply shocks, (2) oil price changes in response to economic activity and (3) pure speculation. Constructing these measures involves estimating a VAR that includes not only the price of oil but also worldwide oil production and measures of economic activity. We replicate his VAR for our (slightly extended) time period of interest.[10] The oil supply shock (1) would be the one we are interested in as it is exogenous to economic activity in the U.S. manufacturing sector. Note that positive innovations to this variable actually *increase* the price of oil i.e. are negative supply shocks. In our regression analysis, we contrast the effect of an exogenous oil supply shock (1) to a "demand shock" (2) that leads to an output expansion also in U.S. manufacturing, higher demand for oil and the higher oil prices. Both shocks raise oil prices but while the former lower labor demand, the latter raises it. As a consequence, the wage dispersion responses to these shocks – though they both raise oil prices – should have opposite signs. As we will see in the regression analysis, this is the case.

Our model implies differences in the response of wage dispersion to oil price shocks across worker skill groups. To test this prediction, we first must define who is a skilled worker or not. This leads us to the other limitation of the ASM, which is that it does not contain data on the most obvious measures of skill. In the CPS, there is information on a person's level of education leading to clear definitions of skill. For the ASM, we choose to define skilled workers as non-production workers and non-skilled as production workers. We will consider the effect on total wages as well as for production workers, hourly wage. We cannot construct a per hourly wage measure for the non-production workers because hours are not reported. The other important decision to be made is what unit of geographic disaggregation should be taken as the relevant one. In the model, we discuss "regions" which is really a standin for some relatively homogeneous geographic unit. For our purposes, we use the county as the relevant unit.[11] This accords well with the evidence that cross-state migration for job purposes is only a fraction of migration across county lines.[12]

2.2 Regression Specification and Results

2.2.1 Evidence of between-county dispersion

We regress various measures of wage dispersion based on different skill groups on contemporaneous and lags of the oil supply shock as well as measures of aggregate economic activity and a time trend to control for any low frequency effects. Specifically, we estimate

$$\sigma_t = \beta_0 + \beta_1 t + \beta_2 OIL_t + \beta_3 Demand_t + \varepsilon_t \tag{4}$$

[10]In particular, we assume that worldwide oil production 1971-1973 grew at he same rate as U.S. oil production.

[11]In principle, we could have chosen any level of disaggregation given the detail in the confidential ASM data, but much finer distinction would run into disclosure restrictions.

[12]We have redone the analysis at the state-level with both the Census and the CPS data and the results are much more muted suggesting to us that the state is to coarse of a geographic unit to really identify the effect.

where σ_t is the between-county dispersion measure, OIL_t the Kilian measure of oil supply shocks and $Demand_t$ the Kilian measure of changes in aggregate demand that drive the oil price. We run a version of equation (4) for each unskilled and skilled wage dispersion.

We calculate both robust and Newey-West autocorrelation robust standard errors allowing for one year of dependence. The Newey-West standard errors are reported in square brackets below the point estimates. The results for unskilled total wages are reported in Table 7. We find fairly robust support for one implication of the theory. In column 1 where we weight establishment-level wages by the number of unskilled workers at the establishment, the dispersion in unskilled wages increases sharply on impact of the shock and the effect persists for one year. This is true in a statistical and economic sense with effects being significant at the 5% level. In interpreting the economic significance, since the dispersion measure is in levels, it is useful to think in terms of standard deviations. Table 3 offers summary statistics for the oil supply and aggregate economic activity measures we constructed as well as the wage dispersion measures. Returning to the regression, we find that a one standard deviation increase in the oil price increases unskilled wage dispersion by 16% of a standard deviation ($0.0438 * 0.0283/0.0079$), a sizable amount. Note that this effect persists for one more year after the oil price shock though the significance declines to 10% confidence. Statistical significance is unaffected if we use Newey-West standard errors reported in square brackets. In column 2, we drop one of the lags. We lose some statistical significance and magnitude of the effect, but the basic pattern remains unchanged. In columns 3 and 4, we redo the regressions without weighting the observations. Results are slightly strengthened in this specification suggesting that oil price shocks appear to have a more varied effect on small establishments. Of independent interest is the fact that consistently across all specifications, demand shocks have a negative effect on dispersion. This again is consistent with our theory that increased economic activity (say, due to a technology shock) raises demand for oil and thus the oil price. Consistent with that would be a positive labor demand shock that would lead to a lower dispersion as shown in the model section.

We also examined the dispersion response of unskilled wages per worker rather than per hour. There are barely any differences which suggests that higher wage dispersion after an oil price shock cannot be exclusively driven by dispersion in hours worked.

If we turn to the results report in Table 8 for skilled wages, then dispersion is basically unaffected by either oil supply shocks or output shocks. This is independent of whether or not we weight based on employment to generate the between county dispersion. Our theory predicts this ordering of responses though the fact that the response of skilled wage dispersion in the data is essentially zero rather than slightly positive is of some tension. We believe that this is partly driven by the fact that we only consider the total wage bill rather than an hourly wage. So the total effect here is potentially confounded by opposing changes in these labor effort variables. In fact, our theory would predict changes in the dispersion of skilled workers in response to oil price shocks.

We also reestimated these regressions with a variety of different measures of oil price shocks.

For example, we have used the "oil price shock dates" suggested by Hoover and Perez (1994) who attempt to identify truly exogenous political events that led to subsequent spikes in oil prices. The Hoover-Perez variable is a dummy taking the value 1 in the case of an exogenous "oil price shock event" (say a politically caused disruption of oil supply such as the 1973 OPEC oil embargo) and 0 otherwise. These dates are 1969, 1971, 1974, 1978, 1980 and 1981; following Bernanke, Gertler and Watson (1997) and Polgreen and Silos (2009) the August 1990 invasion of Kuwait is also included as another Hoover-Perez episode. Results are basically unaffected in terms of statistical significance. The drawback of this specification is in terms of the economic significance where it is difficult to clear interpretation of the magnitude of these effects; also this time series stops in 1991 missing nearly two decades of our data.

2.2.2 Additional Evidence on Wages Across Fuel Efficiency Groups

The previous evidence pertained to the dispersion between the average wages of individual counties. This is the closest empirical analogue of our model. We will go one step further and examine another implication of the model. It would predict that wages fall more in places where oil plays a larger role in production. We estimate this effect at the establishment level by running the following regressions

$$\log w_{it} = \beta_0 + \beta_1 t + \beta_2 OIL_t + \beta_3 Demand_t + \eta_i + \varepsilon_{it} \tag{5}$$

where we differentiate among energy efficient and energy intensive establishments – depending on whether they are above or below the median fuel intensity in the data. We include identical sets of controls as above and estimate version of equation (5) for skilled and unskilled wage levels. If our model is correct and the previous evidence on the response of skilled versus unskilled wages (Polgreen and Silos (2009)) is correct, we would expect skilled wages to decline more than unskilled wages and wage declines to be more pronounced in energy intensive establishments.

This is exactly borne out in the data: skilled wages decline by more than unskilled wages by about a factor of 2.5. The wage decline for both skilled and unskilled wages is stronger in energy intensive establishments where skilled wages fall by about 1% in absolute amounts. The decline in unskilled wages is less than half a percent and statistically insignificant in the pooled OLS regressions. For energy efficient establishments the just mentioned effects are smaller and not as significant for skilled wages. The differences in the estimated coefficient from including establishment fixed effects are minor. These regressions show the direct effect on wage dispersion from oil prices as wages fall dissimilar amounts across these two groups. This is micro-level confirmation of the aggregate fact documented previously by Polgreen and Silos (2009) who explain the decline in the skill premium with an energy-capital-skill complementarity.

3 Theoretical Motivation

We formulate a spatial model where differences in energy intensity, labor reallocation and local housing prices deliver rising unskilled wage dispersion, while skilled wage dispersion rises only moderately or remains stagnant. For tractability, we limit our analysis to two regions although the model could be extended to N regions without affecting the main results.

3.1 Firms and labor demand

We begin by studying the case of fixed labor supply and then allow workers to reallocate in response to oil price shocks. There are two regions,[13] denoted by i and j, regionally separate from one another, and each with a continuum of competitive firms. They produce output and sell it into a world market at a (normalized) fixed price of 1 using the following technology (we describe the model for region i, region j is analogous):

$$y_i = u_i^{\alpha} \Big[\min \{ s_i, \gamma_i e_i \} \Big]^{1-\alpha} \tag{6}$$

where y_i is output, u_i and s_i are unskilled and skilled labor respectively, while e_i is energy consumed. α and γ_i are technology parameters that govern factor shares. γ_i is of particular interest as it determines the energy intensity of firms in region i. The higher γ_i, the more fuel-efficient are firms. Without loss of generality, we assume that $\gamma_i > \gamma_j$. We abstract from technological differences *within* a region and assume that all firms operate the same technology. We could relax that assumption and assume another spatial dimension (within-region heterogeneity) involving commuting between different neighborhoods. Guerrieri, Hartley and Hurst (2009) have shown that this can generate within-region dispersion of housing prices and – in our context – also within-region wage dispersion.

Because we are interested in explaining the general energy-wage dispersion relationship, we focus on *between-region* differences in energy intensity. This focus is supported by the results in Davis, Loungani and Mahidhara (1997) who found vast geographical differences in responses to oil price shocks. We confirm this spatial difference in energy intensity in our Census establishment-level data. As Table 3 shows, energy intensity is not only heterogeneous, but it differs significantly across counties. We consider this evidence a lower bound because we do not account for industry-specific effects.[14] Differences in energy intensity will surely impact labor demand and wage dispersion when oil prices change, so it seems imperative to feature it in our model. We shall see that this difference will explain the movement in wage dispersion without any other technological dispersion or labor market frictions.

We adopt a nested production technology which is special case of Polgreen and Silos (2009)

[13] This term is meant to be vague and simply define regions with different energy intensities.

[14] We conduct this exercise with publicly available data from the Manufacturing Energy Consumption Survey and find vast industry differences in spatial energy intensity dispersion.

who in turn follow Krusell et al. (2000). They employ a nested CES technology where energy and skilled labor feature as complements while unskilled labor and the energy-skill complex are substitutes. This leads to a fall in the skill premium in response to an oil price shock.[15] We want to preserve this result while keeping the analysis tractable, which is why we choose a Cobb Douglas-Leontief formulation. We are aware that the strict complementarity (the min operator) may be an extreme assumption, but none of our qualitative results about wage dispersion within and between skill groups are affected by it. Using a nested constant CES production still delivers a negative oil price-skill premium relationship, but a CES production function makes an analytical solution unobtainable.

Both skilled labor and energy are chosen by the firm in the same period and free of any adjustment constraints. Then the strict complementarity immediately dictates the optimal relationship between the use of energy and skilled labor:

$$e_i = \frac{s_i}{\gamma_i}$$

We can see that for energy-efficient firms the skill-energy ratio will be higher than in energy-inefficient (or energy intensive) firms. Oil prices, q, are determined outside of the model and taken as given by firms. Wages for unskilled, w_i^u, and skilled labor, w_i^s, are also taken as given by firms but will be determined endogenously.

$$w_i^u = \alpha \left(\frac{s_i}{u_i}\right)^{1-\alpha} \tag{7}$$

$$w_i^s = (1-\alpha)\left(\frac{s_i}{u_i}\right)^{-\alpha} - \frac{q}{\gamma_i} \tag{8}$$

We chose the metric of q such that skilled wages are always positive. This is a consequence of our Leontief assumption between skilled labor and energy which in turn leads to the additive term in skilled labor demand.[16] Equation (8) shows that labor demand for skilled workers is higher the less energy-dependent its production (the higher γ_i). Unskilled labor demand, in contrast, is not influenced by oil prices directly, which is a consequence of our Cobb-Douglas assumption between unskilled labor and the other production factors. We now analyze how the skill premium and wage dispersion respond to an oil price shock both without and with migration. The standard definition of the skill premium for region i and the wage dispersion for skill group k are

[15] To be precise, Polgreen and Silos (2009) confirm a well-known capital-skill complementarity and a capital-unskilled substitutability. They go further to show empirically that capital and energy are complements too. Combining these two results implies a skill-energy complementarity and an unskilled-energy substitutability. Without changing the main result about wages of skill groups we omit capital here to simplify the analysis.

[16] Note that the skill premium need not be larger than 1. We could make the skilled relatively scarcer or relatively more efficient to achieve this result, but it has no bearing on how the variables respond to shocks.

$$SP_i \equiv \frac{w_i^s}{w_i^u} = \frac{1-\alpha}{\alpha}\left(\frac{s_i}{u_i}\right)^{-1} - \frac{q}{\alpha\gamma_i}\left(\frac{s_i}{u_i}\right)^{\alpha-1}$$
$$V(w^k) = \sum_i k_i(w_i^k - \overline{w}^k)^2 = k_i(1-k_i)(w_i^k - w_j^k)^2$$

where we've used properties of a bivariate variable. Inspection of the expression for the skill premium and wage dispersion leads us to a preliminary result when labor remains fixed.

Proposition 1 *If energy is more complementary to skilled labor than to unskilled labor (Polgreen and Silos (2009)) and if the allocation of labor is fixed, then an oil price shock*

- *reduces the skill premium (Polgreen and Silos (2009)),*
- *changes the skilled wage dispersion,*
- *does* not *affect unskilled wage dispersion.*

Proof

$$\frac{\partial SP}{\partial q} = -\frac{1}{\alpha\gamma_i}\left(\frac{s_i}{u_i}\right)^{\alpha-1} < 0$$
$$\frac{\partial V(w^s)}{\partial q} = 2s_i s_j(w_i^s - w_j^s)\left(\frac{\gamma_i - \gamma_j}{\gamma_i\gamma_j}\right).$$

For the second part of the proposition, with differences in γ the downward shift in skilled labor demand in energy-efficient regions (high γ) will be less pronounced than in energy-inefficient regions. Holding labor supply fixed this means that skilled wages across regions would become more dispersed ($|w_i^s - w_j^s|$ increases) if originally $w_i^s > w_j^s$ and less dispersed ($|w_i^s - w_j^s|$ decreases) if originally $w_i^s < w_j^s$. Finally, in contrast to skilled wage dispersion, unskilled wage dispersion does not change at all because the demand curve for unskilled labor does not change as one can see from equation (7). ∎

This first part of result holds as long as skilled labor and energy are more complementary than unskilled labor and energy.[17] As mentioned above, the demand curve for skilled labor shifts down in all regions, while the demand curve for unskilled labor does not shift at all. With a fixed labor

[17] Suppose the production function is a nested CES $y = \left\{\alpha u^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left[(1-\gamma)s^{\frac{\eta-1}{\eta}} + \gamma e^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}\frac{\sigma-1}{\sigma}}\right\}^{\frac{\sigma}{\sigma-1}}$ where η is the elasticity of substitution between skilled labor and energy and σ that between unskilled labor and the skilled/energy complex. Then, $\frac{w^s}{w^u} = \frac{(1-\alpha)(1-\gamma)}{\alpha}\left[1-\gamma+\gamma\left(\frac{\gamma}{1-\gamma}\frac{w^s}{q}\right)^{\eta-1}\right]^{\frac{\sigma-\eta}{\sigma(\eta-1)}}\left(\frac{s}{u}\right)^{-\frac{1}{\sigma}}$ and $sign\left(\frac{\partial(w^s/w^u)}{\partial q}\right) = sign(\eta-\sigma)$; i.e. if energy is more substitutable with unskilled labor than with skilled ($\eta < \sigma$) then an oil price shock

supply, skilled wages fall everywhere and unskilled wages stay constant thus depressing the skill premium.

Proposition 1 shows that without changes in the *allocation* of labor across regions changes in the dispersion of unskilled wages cannot be explained by differences in energy intensity and subsequent changes in labor demand alone. Also, depending on the assumed exogenous labor supply, skilled wage dispersion may counterfactually decrease. These two arguments highlight the need to explicitly model labor supply and how it endogenously responds to oil prices in light of differences in energy intensity.

3.2 Households

There is a measure 1 of both unskilled and skilled workers in the economy. Each worker first decides in which region to reside and work. We make the common assumption that workers inelastically supply their labor in whatever region they reside. A worker from skill group k residing in region i is paid real wage w_i^k which he uses to purchase consumption goods c_i^k and "housing"[18] h_i^k. Consumption is our numéraire and it is traded on a world market which is big enough so changes in local demand do not impact the price. The price of one unit of housing in terms of consumption is r_i. In contrast to consumption, housing is a locally produced and supplied good and we require workers to purchase their housing in the same region where they work and reside. They maximize the following utility function

$$u(h^k, c^k) = (h_i^k)^{\theta^k} (c_i^k)^{1-\theta^k}$$
$$\text{s.t. } c_i^k + r_i h_i^k \leq w_i^k$$

will result in energy being substituted by unskilled labor depressing the skill premium.

$$q = (1-\alpha)\gamma \left\{ \alpha + (1-\alpha) \left[(1-\gamma) \left(\frac{s}{u}\right)^{\frac{\eta-1}{\eta}} + \gamma \left(\frac{s}{u}\frac{e}{s}\right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}\frac{\sigma-1}{\sigma}} \right\}^{\frac{1}{\sigma-1}} \left[(1-\gamma) \left(\frac{s}{u}\right)^{\frac{\eta-1}{\eta}} + \gamma \left(\frac{s}{u}\frac{e}{s}\right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\sigma-\eta}{\sigma(\eta-1)}} \left(\frac{s}{u}\right)^{-\frac{1}{\eta}} \left(\frac{e}{s}\right)$$

$$w^s = (1-\alpha)(1-\gamma) \left\{ \alpha + (1-\alpha) \left[(1-\gamma) \left(\frac{s}{u}\right)^{\frac{\eta-1}{\eta}} + \gamma \left(\frac{s}{u}\frac{e}{s}\right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}\frac{\sigma-1}{\sigma}} \right\}^{\frac{1}{\sigma-1}} \left[(1-\gamma) \left(\frac{s}{u}\right)^{\frac{\eta-1}{\eta}} + \gamma \left(\frac{s}{u}\frac{e}{s}\right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\sigma-\eta}{\sigma(\eta-1)}} \left(\frac{s}{u}\right)^{-\frac{1}{\eta}}$$

$$w^u = \alpha \left\{ \alpha + (1-\alpha) \left[(1-\gamma) \left(\frac{s}{u}\right)^{\frac{\eta-1}{\eta}} + \gamma \left(\frac{s}{u}\frac{e}{s}\right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}\frac{\sigma-1}{\sigma}} \right\}^{\frac{1}{\sigma-1}}$$

[18] We use the term housing for simplicity, but really we have in mind nontradeables produced locally in region i.

where θ^k is the expenditure share of housing in skill group k. The first order conditions give rise to the following demand curves for housing and consumption

$$r_i h_i^k = \theta^k w_i^k \tag{9}$$
$$c_i^k = (1-\theta^k) w_i^k. \tag{10}$$

We want to point out that both skill groups consume the same goods though the quantity will vary with income levels (w^k) and preferences (θ^k). Thus, we can write aggregate demand for housing and consumption in region i as

$$\begin{aligned} H_i^D &= h_i^u u_i + h_i^s s_i \\ &= \frac{\theta^u w_i^u}{r_i} u_i + \frac{\theta^s w_i^s}{r_i} s_i \end{aligned} \tag{11}$$
$$\begin{aligned} C_i^D &= c_i^u u_i + c_i^s s_i \\ &= (1-\theta^u) w_i^u u_i + (1-\theta^s) w_i^s s_i \end{aligned} \tag{12}$$

The market for housing is local and the price of housing, r_i, may differ across regions. Following the urban literature (see for example Notowidigdo (2010)) we assume that housing is supplied by landlords who are not active in labor or goods markets.[19] Since we do not explicitly model their objective, we simply assume that the resulting supply curve of housing in region i is

$$r_i = h_i^\beta \tag{13}$$

where we assume that $\beta > 0$.[20] Contrary to the (implicit) consumption supply curve which is flat, the housing supply curve slopes upward. This reflects the property that housing is in scarce supply at least in the short run.[21] Housing prices respond to demand and are, hence, the key determinant

[19] We may also assume that skilled high-income workers own houses which would make the model's predictions about wage dispersion more pronounced: skilled workers would reallocate even faster to high-wage regions since their income loss is even higher. The models prediction about wage dispersion would only weaken if we unplausibly assumed that unskilled workers own houses and skilled workers do not.

[20] Again, we could explicitly model housing being produced by the local firm (alongside the intermediate good that goes into final production). We would still have an upward sloping supply curve which is important as it shapes households' migration decision.

[21] There has been a long debate if spatial differences in housing prices are determined by supply-side or demand-side factors. Differences in housing regulations (see Glaeser, Gyourko and Saks (2005*b*,*a*)) or geographical limitations (see Saiz (2010)) are examples of the former view. We follow the approach of Rosen (1979), Roback (1982), Moretti (2013) and van Nieuwerburgh and Weill (2010) and assume that spatial housing price dispersion is predominantly demand-driven by in- and out-migration of workers who are attracted by conditions of the local labor market. Guerrieri, Hartley and Hurst (2009) have also shown that this approach has the potential to explain within-region housing price dispersion although we do not focus on that issue. We leave it open if the supply curve is convex ($\beta > 1$) or concave ($\beta < 1$) as found by Notowidigdo (2010). Our model will deliver the same qualitative results as long as the supply curve slopes up.

of a household's purchasing power and utility. Together with wages, housing prices hence determine in which region the household will supply its labor.

Combining equations (11) and (13) the equilibrium housing price in region i is

$$\begin{aligned} H_i^S(r_i^*) &= H_i^D(r_i^*) \\ r_i^* &= \left[\frac{\theta^u w_i^u}{r_i^*} u_i + \frac{\theta^s w_i^s}{r_i^*} s_i\right]^{\beta} \\ r_i^* &= \left[\theta^u w_i^u u_i + \theta^s w_i^s s_i\right]^{\frac{\beta}{1+\beta}} \end{aligned} \tag{14}$$

Note that the equilibrium a region's housing price is increasing in the number of people living in the region $(s_i + u_i)$. For the solution of the endogenous supply of labor, it is convenient to know the ratio of economy-wide housing prices

$$\frac{r_i}{r_j} = \left\{ \frac{\left[1 + \tilde{\theta} \frac{w_i^s s_i}{w_i^u u_i}\right]}{\left[1 + \tilde{\theta} \frac{w_j^s s_j}{w_j^u u_j}\right]} \frac{w_i^u u_i}{w_j^u u_j} \right\}^{\frac{\beta}{1+\beta}} \tag{15}$$

where $\tilde{\theta} \equiv \theta^s / \theta^u$.

3.3 Labor reallocation

Workers can migrate from region i to region j at no cost. Then consider a household in region j that thinks about migrating to region i (or vice versa). Using the above demand curves (Eqns. (9) and (10)), she compares her indirect utility in both regions given the respective wage offers and housing prices. The indirect utility can be written as

$$v(c_i^k, h_i^k) = \left(\frac{\theta^k}{r_i}\right)^{\theta^k} (1 - \theta^k)^{1-\theta^k} w_i^k$$

In equilibrium, she must be indifferent between staying and moving:

$$v(c_i^k, h_i^k) = v(c_j^k, h_j^k) \tag{16}$$

This implies that housing price ratios have to be equal to functions of wage ratios for skilled and unskilled workers.

$$\frac{r_i}{r_j} = \left(\frac{w_i^u}{w_j^u}\right)^{\frac{1}{\theta^u}} \quad \text{and} \tag{17}$$

$$\frac{r_i}{r_j} = \left(\frac{w_i^s}{w_j^s}\right)^{\frac{1}{\theta^s}} \tag{18}$$

Equations (17) and (18) have to hold in equilibrium. Plugging in equations (7), (8) and (15) gives two equilibrium conditions. Noting that $1 = u_i + u_j = s_i + s_j$ these two conditions determine the equilibrium allocation of skilled and unskilled labor across regions $\{s_i, u_i\}$. At this allocation, an individual unskilled or skilled worker is indifferent to migrating to the other region, household utility and firm profits are maximized. Equations (7) and (8) determine equilibrium wages, equation (14) equilibrium housing prices, and equations (11) and (12) housing and consumption quantities in all regions.

3.4 The impact of an oil price shock

If energy is costless ($q = 0$) or if both regions have the same energy intensity ($\gamma_i = \gamma_j$), then the resulting equilibrium allocation is balanced: $s_i = s_j = u_i = u_j = 1/2$.[22] The conditions governing equilibrium, equations (7), (8), (14), (17) and (18), imply that there are no wage or rent differences between regions. Hence, there is no wage and housing price dispersion. With differences in energy intensity, positive oil prices matter for the allocation of labor, wages and housing prices. In particular, the allocation of labor is skewed in favor of the more energy-efficient region, which has higher wages for all skill groups and also higher housing prices. For convenience let

$$\tilde{s}_\ell = \frac{s_\ell}{u_\ell} \qquad \ell = i, j$$

Note that given $\tilde{s}_i, \tilde{s}_j$, we can express actual employment levels for each skill group:

$$u_i = \frac{1 - \tilde{s}_j}{\tilde{s}_i - \tilde{s}_j}$$
$$s_i = \frac{\tilde{s}_i(1 - \tilde{s}_j)}{\tilde{s}_i - \tilde{s}_j}$$

Using these expressions, we can rewrite the two no-migration conditions that define the solution for $\tilde{s}_i$ and $\tilde{s}_j$.

[22] It's trivial to check that this allocation satisfies the equations for $q = 0$.

$$\left(\frac{\tilde{s}_i}{\tilde{s}_j}\right)^{\frac{(1-\alpha)}{\tilde{\theta}}} = \frac{\tilde{s}_i^{-\alpha}(1-\alpha) - \frac{q}{\gamma_i}}{\tilde{s}_j^{-\alpha}(1-\alpha) - \frac{q}{\gamma_j}} \tag{19}$$

$$\left(\frac{\tilde{s}_i}{\tilde{s}_j}\right)^{\frac{(1-\alpha)}{\theta_u}} = -\left[\frac{\tilde{s}_i(1-\tilde{s}_j)}{\tilde{s}_j(1-\tilde{s}_i)}\left(\frac{\tilde{s}_i^{-\alpha}(\alpha\tilde{\theta}+1-\alpha) - \frac{q}{\gamma_i}}{\tilde{s}_j^{-\alpha}(\alpha\tilde{\theta}+1-\alpha) - \frac{q}{\gamma_j}}\right)\right]^{\frac{\beta}{1+\beta}} \tag{20}$$

where $\tilde{\theta} = \theta_u/\theta_s$. Now we can show that skilled will concentrate in the energy-efficient region more than unskilled do.

Proposition 2 *For any positive oil price the equilibrium skill intensity, wages and rents are higher in the energy-efficient region: If $q > 0$ and $\gamma_i > \gamma_j$, then $\tilde{s}_i > \tilde{s}_j$, $w_i^s > w_j^s$, $w_i^u > w_j^u$ and $r_i > r_j$.*

Proof First note that $\tilde{s}_i > \tilde{s}_j \Leftrightarrow s_i > u_i \Leftrightarrow \frac{s_i}{u_i} = \tilde{s}_i > 1$.

Now we prove that $\tilde{s}_i > \tilde{s}_j$. Assume otherwise, i.e. $\tilde{s}_i < 1 < \tilde{s}_j$, then the no-migration condition, equation (19), does not hold: If $\tilde{s}_i < \tilde{s}_j$, then the LHS is smaller than 1, but the RHS is greater than 1. To see the latter, note that $\tilde{s}_i < \tilde{s}_j \Leftrightarrow \tilde{s}_i^{-\alpha} > \tilde{s}_j^{-\alpha}$. Because we assumed region i to be more energy-efficient, $\gamma_i > \gamma_j \Leftrightarrow \frac{-q}{\gamma_i} > \frac{-q}{\gamma_j}$. Thus, both terms in the numerator of the RHS are greater than the analogous terms in the denominator, so the RHS is greater than 1.

Substituting this result into equation (7) shows that $w_i^u > w_j^u$. Equation (17) delivers the result for housing prices and equation (18) the result for skilled wages. ∎

The intuition here is quite clear. Because the skilled are complements to energy, it is profitable to have relatively more of them where energy is used most efficiently. Because skilled and unskilled labor are complements, it is more profitable to have many unskilled workers around where skilled workers are. Because both skilled and unskilled workers concentrate in the energy-efficient region, this high demand for housing will drive up rents while slack demand for housing in the energy-inefficient city will lead to low rents.[23]

Proposition 3 *In the energy-efficient region, an oil price shock increases the skill intensity for small oil prices, decreases the skill premium; in the energy-inefficient region, an oil price shock decreases the skill intensity while the response of the skill premium is ambiguous: $\frac{\partial \tilde{s}_j}{\partial q} < 0$, $\frac{\partial \tilde{s}_i}{\partial q} > 0$ for q not too large[24] and $\frac{\partial \tilde{s}^i}{\partial q} < 0$.*

Proof We know that for $q = 0$ the skill intensity in both regions is unity. For any positive oil price, however, $\tilde{s}_i > 1$; therefore, $\frac{\partial \tilde{s}_i}{\partial q} > 0$ for q around 0. Similarly, $\frac{\partial \tilde{s}_j}{\partial q} < 0$ for small q.[25]

[23] We can develop some comparative statics results for how skilled-unskilled ratios change with q. A fully characterized linearized solution of the model is provided in the appendix.

[24] At some places in the paper, we refer to q as "not too large". This is because we focus on the empirically plausible case of a fairly balanced allocation. If q gets too large, then all economic activity concentrates in the most energy efficient region – a case that clearly looks like an artifact, especially given the constant technologies we assume.

[25] This result actually holds globally for all levels of q.

Note the skill premium in the energy-efficient region is $SP_i = \frac{1-\alpha}{\alpha}\tilde{s}_i^{-1} - \frac{q}{\alpha\gamma_i}\tilde{s}_i^{\alpha-1}$. When q rises, the skill premium falls because labor demand falls; when additionally skilled labor supply adjusts ($\tilde{s}_i$ increases due to in-migration), the skill premium decreases further.

As for the skill premium in the energy-inefficient region a negative relative labor demand shift and a negative relative supply shift counteract each other, so it is not possible to determine the direction of the skill premium analytically. In our numerical simulations in the appendix it appears that the labor demand shift dominates.[26] ∎

The economy-wide skill premium is a weighted average of the two regions' skill premia. Because the energy-efficient region (where the skill premium falls for sure) attracts more people overall, the negative effect in that region will dominate the possibly positive one in the energy-inefficient region, so the overall skill premium will most likely fall as shown in Figure 5.

We point out some interesting comparative statics here. First, larger differences in energy intensity $(\gamma_i - \gamma_j)$ increase the effect of oil price shocks. The bigger the energy intensity gap, the greater the pressure to reallocate in the face of a standard deviation shock to oil prices. Skilled workers reallocate very quickly compared to unskilled workers. The energy-skill complementarity in our production technology is behind this asymmetry. The asymmetric effect of oil price shocks on skilled to unskilled labor reallocation are accentuated by large differences in how the two skill groups value housing. If $\theta_u \gg \theta_s$, then the unskilled are even less likely to move with the skilled as they value affordable housing much more. One thing to note is that β, the elastic region of the housing supply curve, does not affect the asymmetry. Instead more inelastic supply curves slow reallocation.

Now we are in position to derive our central result.

Proposition 4 *An increase in the oil prices increases both unweighted and weighted unskilled wage dispersion if oil prices are not too large:* $\frac{\partial(w_i^u - w_j^u)}{\partial q} > 0$ *and* $\frac{\partial V(w^u)}{\partial q} > 0$ *for q not too large.*

Proof Recall the expression for unweighted and weighted wage dispersion

$$w_i^u - w_j^u = \alpha\left(\tilde{s}_i^{1-\alpha} - \tilde{s}_j^{1-\alpha}\right)$$
$$V(w^u) = u_i(1-u_i)(w_i^u - w_j^u)^2$$

Note that for $q = 0$ both unweighted and weighted wage dispersion are nil. From Proposition 2 we know that $\frac{\partial\tilde{s}_i}{\partial q} > 0$ and $\frac{\partial\tilde{s}_j}{\partial q} < 0$, so the unweighted wage dispersion across regions rises. This also pushes up weighted wage dispersion. For an analysis of the linearized version see appendix. ∎

For the skilled, the result is a bit more subtle.

Proposition 5 *Skilled wage dispersion increases by less than unskilled wage dispersion after an oil price shock:* $0 < \frac{\partial \log V(w^s)}{\partial q} < \frac{\partial \log V(w^u)}{\partial q}$.

[26] Keep in mind that the inward relative labor demand shift is much stronger in the energy-inefficient region.

Proof For $\frac{\partial V(w^s)}{\partial q}$ analogous to proof of Proposition 3, for $\frac{\partial V(w^s)}{\partial q} < \frac{\partial V(w^u)}{\partial q}$ see appendix. ∎

The logic of our last two results is as follows. If oil prices q rise, then the labor demand for skilled shifts inwards suppressing skilled wages in both regions. The fact that only the skilled labor demand curve decreases is due to energy and skilled labor being strict complements. The demand curve for unskilled labor does not shift because unskilled labor and energy/skilled labor have a unit elasticity of substitution. This above-described inward shift is comparatively weak in region i, which is more energy-efficient ($\gamma_i > \gamma_j$). Hence, there will be migration pressure for skilled workers to move to region i. This migration increases the ratio of skilled to unskilled labor in region i and makes unskilled labor relatively scarce in region i. Therefore, some unskilled workers now follow the skilled migrants to region i where they can earn a higher wage. Behold that unskilled migration is much weaker than skilled migration because it just responds to an abundance of skilled workers in the energy-efficient region and is not directly affected by an oil price shock. Although unskilled follow skilled workers, the ratio of skilled to unskilled labor, s_i/u_i, in the new equilibrium will be still higher than in the old one.

Overall migration increases housing demand in region i driving up housing prices r_i, so, eventually, migration comes to a stop when housing prices are so high that further migration would not increase utility of a worker although he would get a higher wage in region i. Lower housing prices in region j due to skilled out-migration are like a positive externality for unskilled that makes them more inclined to stay despite lower wages.[27]

These changes in labor supply (migration) and labor demand produce a widening range of unskilled wages, $w_i^u - w_j^u$, and housing prices, $r_i - r_j$. Thus, unskilled (unweighted) wage dispersion and housing price dispersion increases (see Figure 6). Moreover, weighted wage dispersion also increases because there is little migration of this group (see Figure 4). Unskilled workers migrate very little. Skilled migration, in contrast, is fairly pronounced and arbitrages away much of the skilled wage differential. Hence, even though there are large changes in the allocation of skilled workers, this has little impact on skilled weighted wage dispersion because the range of skilled wages is so low. Note the interesting general equilibrium effect on wage dispersion here. Even though the initial incidence of the oil price shock falls most strongly on the skilled due to complementarities, they, in the end, see the least impact on wage dispersion because they adjust their labor supply.

We now present the result of some numerical simulations to offer an example of this process. The most relevant variables are plotted as a function of the oil price q in Figures 3-6. We can see that the local results derived above hold for a fairly large range of q. It's only when oil prices are so large that the overwhelming majority of workers reside in the energy-efficient region already and wages and housing prices from the other region don't matter much for overall wage (housing price)

[27]Housing prices may dampen unskilled migration for another reason: If they spend a higher fraction of their income on housing than skilled workers do (as has been shown in other work), then they are more sensitive to the higher housing prices in the destination region and less inclined to migrate. But we do not pursue this here.

dispersion that dispersion may not increase further. In the limiting case, when all workers live in the energy-efficient region wage dispersion converges back to 0. We find this situation somewhat too extreme to be empirically relevant.

Lastly, we discuss the quantitative scale of migration which we assume to also comprise spatial differences in entry and exit into the labor force. It seems plausible to think that labor demand responds rather quickly to an oil price shock, but is it also plausible to think that after an oil price shock workers give up a (worse paying) job in one region to migrate to another one? According to the "Labor Force Status Flows" (Bureau of Labor Statistics (2010)) about 4-5% of the labor force turn over annually due to retirement or entry into the labor force. It is reasonable to assume that most of the entrants into the labor force trade off job offers against local living expenses and move to a place where they receive the most favorable wage-living costs bundle.

In addition to pure entry and exit into the labor force there is pure migration. According to the 2000 Census, 120 million Americans moved between 1995 and 2000. Assuming a constant migration per year and the same migration pattern for people in the labor force, pure reallocation as migration corresponds to 9% of the labor force. Thus, labor reallocation in the broad sense add up to a considerable portion (about 15%) of the labor force. If oil prices drive only a small fraction of this reallocation, it could still have an outsized impact on wage levels and dispersion.

4 Conclusion

We have established a new stylized fact: oil prices and the dispersion of unskilled wages are positively correlated. A large macroeconomics literature has long paid attention to the effect of oil prices on macroeconomic aggregates such as output, investment, inflation etc. (see for example Hamilton (1983), Kim and Loungani (1992), Kilian (2009)). While existing research on oil prices and labor markets has focused on explaining the response of the aggregate wage level or the wage level of different skill groups (as in Polgreen and Silos (2009)), we provide a model that can match both the level and the higher moments of wages between and within skill groups. Explaining wage dispersion in particular, requires that oil prices operate not only as a usual adverse shock to production factor but as a shock to local labor supply. In our model, firm differences in energy intensity lead to an asymmetric response of labor demand driving up wage dispersion. In a world with perfect labor markets and homogeneous living expenses labor reallocation would offset this wage dispersion. A large literature in labor economics has studied which imperfections in labor markets can explain wage dispersion and sluggish reallocation. Here we chose a fixed local good consumed by both groups. Oil price shocks induced strong reallocation of skilled workers which kept skilled wage dispersion in check. Unskilled workers, in contrast, migrate much less because they benefit from externalities of skilled migration in terms of lower local living expenses.

We argued that labor supply decisions are mostly shaped by a trade off between wages and living expenses. In particular, unskilled migration is mostly prevented by lower housing prices in regions where firms operate energy-intensive technologies and higher housing prices in more energy-efficient regions. Our model predicts that housing price dispersion should increase in the wake of an oil price shock as well. We leave this aspect of our model to future research. We believe that more can be learned about studying dispersion in local living costs and its interaction with labor markets. In particular, we show how one can use the dynamics of higher-order moments for identification purposes. While labour demand operates in a specific way that should affect the levels and dispersion of wages in the same way, labor supply movements alters the picture on wage dispersion. In that way, using the information on the dynamics of both first and second moments of wages help tell apart labor demand and supply disturbances otherwise confounded in the average wages.

References

Arellano, Cristina, Yan Bai, and Patrick J. Kehoe. 2010. "Financial Markets and Fluctuations in Uncertainty." *Federal Reserve Bank of Minneapolis Staff Report.*

Bernanke, Ben S., Mark Gertler, and Mark W. Watson. 1997. "Systematic Monetary Policy and the effects of Oil Price Shocks." *Brookings Papers on Economic Activity*, 1997(1): 91–157.

Bloom, Nicholas. 2009. "The Impact of Uncertainty Shocks." *Econometrica*, 77(3): 623–685.

Bloom, Nicholas, Max Floetotto, Nir Jaimovich, Itay Saporta-Eksten, and Stephen Terry. 2012. "Really Uncertain Business Cycles." *NBER Working Paper No. 18245.*

Bureau of Labor Statistics. 2007. *Handbook of Methods.* U.S. Department of Labor.

Bureau of Labor Statistics. 2010. *Current Population Survey – Labor Force Status Flows by Sex 1990-2010.* U.S. Department of Labor.

Christiano, Lawrence J., Mathias Trabandt, and Karl Walentin. 2010. "Introducing Financial Frictions and Unemployment into a Small Open Economy Model." *Sveriges Riksbank Working Paper Series 214.*

Davis, Steven J., and John C. Haltiwanger. 1999. "On the Driving Forces Behind Cyclical Movements in Employment and Job Reallocation." *American Economic Review*, 89(5): 1234–1258.

Davis, Steven J., and John C. Haltiwanger. 2001. "Sectoral Job Creation and Destruction Responses to Oil Price Changes." *Journal of Monetary Economics*, 48(3): 465–512.

Davis, Steven J., Prakash Loungani, and Ramamohan Mahidhara. 1997. "Regional Labor Fluctuations: Oil Shocks, Military spending, and Other Driving Forces." *International Finance Discussion Papers No. 578.*

Edelstein, Paul, and Lutz Kilian. 2009. "How Sensitive are Consumer Expenditures to Retail Energy Prices?" *Journal of Monetary Economics*, 56(6): 766–779.

Frey, William H. 2009. "The Great American Migration Slowdown." Brookings Institution.

Garin, Julio, Michael Pries, and Eric Sims. 2011. "Reallocation and the Changing Nature of Economic Fluctuations." *Working Paper.*

Glaeser, Edward L., Joseph Gyourko, and Raven E. Saks. 2005*a*. "Why Have Housing Prices Gone Up?" *American Economic Review Papers and Proceedings*, 95(2): 329–333.

Glaeser, Edward L., Joseph Gyourko, and Raven Saks. 2005*b*. "Why Is Manhattan so Expensive? Regulation and the Rise in Housing Prices." *Journal of Law and Economics*, 48(2): 331–369.

Guerrieri, Veronica, Daniel Hartley, and Erik Hurst. 2009. "Endogenous Gentrification and Housing Price Dynamics." *Working Paper.*

Hamilton, James D. 1983. "Oil and the Macroeconomy since World War II." *Journal of Political Economy*, 91(2): 228–248.

Hamilton, James D. 2003. "What is an oil price shock?" *Journal of Econometrics*, 113(2): 363–398.

Hoover, Kevin D., and Stephen J. Perez. 1994. "Post hoc ergo propter once more: An evaluation of 'Does monetary policy matter?' in the Spirit of James Tobin." *Journal of Monetary Economics*, 34(1): 47–74.

Kambourov, Gueorgui, and Iourii Manovskii. 2009*a*. "Occupational Mobility and Wage Inequality." *Review of Economic Studies*, 76(2): 731–759.

Kambourov, Gueorgui, and Iourii Manovskii. 2009*b*. "Occupational Specificity of Human Capital." *International Economic Review*, 50(1): 63–115.

Keane, Michael P., and Eswar S. Prasad. 1996. "The Employment and Wage Effects of Oil Price Changes: A Sectoral Analysis." *Review of Economics and Statistics*, 78(3): 389–400.

Kilian, Lutz. 2008. "A Comparison of the Effects of Exogenous Oil Supply Shocks on Output and Inflation in the G7 Countries." *Journal of the European Economic Association*, 6(1): 78–121.

Kilian, Lutz. 2009. "Not all Oil Price Shocks are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market." *American Economic Review*, 99(3): 1053–1069.

Kilian, Lutz, and Cheolbeom Park. 2011. "The Impact of Oil Price Shocks on the U.S. Stock Market." *International Economic Review*, 50(4): 1267–1287.

Kilian, Lutz, and Robert Vigfusson. 2011. "Are the Responses of the U.S. Economy Asymmetric in Energy Price Increases and Decreases?" *Quantitative Economics*, 2(3): 419–453.

Kilian, Lutz, and Robert Vigfusson. forthcoming. "Do Oil Prices Help Forecast U.S. Real GDP? The Role of Nonlinearities and Asymmetries." *Journal of Business and Economic Statistics.*

Kim, In-Moo, and Prakash Loungani. 1992. "The Role of Energy in Real Business Cycle Models." *Journal of Monetary Economics*, 29(2): 173–189.

Krusell, Per, Lee E. Ohanian, José-Víctor Ríos-Rull, and Giovanni L. Violante. 2000. "Capital-Skill Complementarity and Inequality: A Macroeconomic Analysis." *Econometrica*, 68(5): 1029–53.

Lee, Kiseok, and Shawn Ni. 2002. "On the Dynamic Effects of Oil Price Shock: A Study Using Industry Level Data." *Journal of Monetary Economics*, 49(4): 823–852.

Lilien, David M. 1982. "Sectoral Shifts and Cyclical Unemployment." *Journal of Political Economy*, 90(4): 777–793.

Loungani, Prakash. 1986. "Oil Price Shocks and the Dispersion Hypothesis." *Review of Economics and Statistics*, 68(3): 536–539.

Molloy, Raven, Christopher L. Smith, and Abigail Wozniak. 2011. "Internal Migration in the United States." *Journal of Economic Perspectives*, 25, Number 2—Spring 2011—Pages 1–42(2): 1–42.

Moretti, Enrico. 2013. "Real Wage Inequality." *American Economic Journal: Applied Economics*, 5(1): 65–103.

Notowidigdo, Matthew J. 2010. "The Incidence of Local Labor Demand Shocks." *Working Paper.*

Polgreen, Linnea, and Pedro Silos. 2009. "Crude Substitution: The Cyclical Dynamics of Oil Prices and the Skill Premium." *Journal of Monetary Economics*, 56(3): 409–418.

Roback, Jennifer. 1982. "Wages, Rents, and the Quality of Life." *Journal of Political Economy*, 90(6): 1257–1278.

Rosen, Sherwin. 1979. "Wage-based Indexes of Urban Quality of Life." In *Current Issues in Urban Economics.* , ed. Peter Mieszkowski and Mahlon Straszheim. Johns Hopkins University Press.

Rupert, Peter, Elena Stancanelli, and Etienne Wasmer. 2009. "Commuting, Wages and Bargaining Power." *Working Paper.*

Saiz, Albert. 2010. "The Geographic Determinants of Housing Supply." *Quarterly Journal of Economics*, 125(3): 1253–1296.

Shimer, Robert. 2007. "Mismatch." *American Economic Review*, 97(4): 1074–1101.

van Nieuwerburgh, Stijn, and Pierre-Olivier Weill. 2010. "Why Has House Price Dispersion Gone Up?" *Review of Economic Studies*, 77(4): 1567–1606.

Wasmer, Etienne, and Yves Zenou. 2006. "Equilibrium Search Unemployment with Explicit Spatial Frictions." *Labour Economics*, 13(2): 143–165.

A Proofs

Proposition 6 *[Linearized Solution] An approximate solution for $\tilde{s}_i, \tilde{s}_j$ around 1 is given by*

$$\tilde{s}_i - 1 = \frac{\omega_i \omega_j^2 \tilde{\theta} q \left(\frac{1}{\gamma_j} - \frac{1}{\gamma_i}\right)}{(\omega_j^2 + \omega_i^2)(1-\alpha)} > 0 \tag{21}$$

$$\tilde{s}_j - 1 = -\frac{\tilde{\theta} q \omega_i^2 \omega_j \left(\frac{1}{\gamma_j} - \frac{1}{\gamma_i}\right)}{(\omega_j^2 + \omega_i^2)(1-\alpha)} < 0 \tag{22}$$

where

$$\omega_k = \frac{1}{\alpha\tilde{\theta} + 1 - \alpha - \frac{q}{\gamma_k}}$$

Proof We take a linear approximation about $\tilde{s}_j = \tilde{s}_i = 1$ to equations (19) and (20):

$$\frac{q}{\gamma_i} + \frac{1-\alpha}{\tilde{\theta}\omega_i}(\tilde{s}_i - 1) = \frac{q}{\gamma_j} + \frac{1-\alpha}{\tilde{\theta}\omega_j}(\tilde{s}_j - 1)$$

$$-\omega_i(\tilde{s}_i - 1) = \omega_j(\tilde{s}_j - 1)$$

Note that $\omega_k > 0$ for all k by our technical assumption on parameters and the oil price. Solving these two linear equations delivers the result. ∎

Proof of Proposition 3: $\frac{\partial \tilde{s}_i}{\partial q} > 0$ and $\frac{\partial \tilde{s}_j}{\partial q} < 0$ for q not too large

For not too large oil prices our approximation is valid. So we differentiate equation (21) with respect to the oil price. Note that $\omega_i < \omega_j$ and that $\omega_k^{'} \equiv \frac{\partial \omega_k}{\partial q} = \frac{1}{\gamma_k}\omega_k^2 > 0$.

$$\frac{\partial \tilde{s}_i}{\partial q} = \frac{\tilde{\theta}\left(\frac{1}{\gamma_j} - \frac{1}{\gamma_i}\right)}{1-\alpha} \left\{ \frac{\omega_i \omega_j^2}{\omega_i^2 + \omega_j^2} + q \left[\frac{(\omega_i^2 + \omega_j^2)(\omega_j^2 \omega_i' + 2\omega_i \omega_j \omega_j') - 2\omega_i \omega_j^2 (\omega_j \omega_j' + \omega_i \omega_i')}{\left(\omega_i^2 + \omega_j^2\right)^2} \right] \right\}$$

$$= \frac{\tilde{\theta}\left(\frac{1}{\gamma_j} - \frac{1}{\gamma_i}\right)}{1-\alpha} \left\{ \frac{\omega_i \omega_j^2}{\omega_i^2 + \omega_j^2} + q \left[\frac{2\omega_i^3 \omega_j \omega_j' + \omega_j^2 \omega_i' \left(\omega_j^2 - \omega_i^2\right)}{\left(\omega_i^2 + \omega_j^2\right)^2} \right] \right\}$$

$$= \tilde{s}_i \left[\frac{1}{q} + \frac{2\gamma_i \omega_i^2 \omega_j + \gamma_j \omega_i (\omega_j^2 - \omega_i^2)}{\gamma_i \gamma_j (\omega_i^2 + \omega_j^2)} \right] > 0.$$

Note totally differentiating $\tilde{s}_i$ implies

$$\frac{d\tilde{s}_i}{dq} = \frac{d\left(\frac{s_i}{u_i}\right)}{dq} = \frac{1}{u_i}\left[ds_i - \frac{s_i}{u_i} du_i\right]$$

$$\text{which implies} \quad \frac{ds_i}{dq} > \frac{du_i}{dq}$$

For the skill intensity in region j we totally differentiate this expression

$$\frac{d\left(\frac{1-s_i}{1-u_i}\right)}{dq} = \frac{-1}{1-u_i}\frac{ds_i}{dq} + \frac{1-s_i}{(1-u_i)^2}\frac{du_i}{dq}$$

$$= \frac{-1}{1-u_i}\left[\frac{ds_i}{dq} - \frac{1-s_i}{1-u_i}\frac{du_i}{dq}\right]$$

Because $\frac{1-s_i}{1-u_i} < 1$ and $\frac{ds_i}{dq} > \frac{du_i}{dq}$ we know that the term in the brackets is strictly positive, thus the entire expression negative, so that $\frac{\partial \tilde{s}_j}{\partial q} < 0$. ∎

Proof of Proposition 5: $\frac{\partial Var(w^u)}{\partial q} > 0$ For simplicity we show that in the approximation $\frac{\partial \log[V(w^u)]}{\partial q} > 0$. Because the logarithm is monotone transformation, this implies that $V(w^u)$ itself is increasing in the oil price as well.

$$\log[V(w^u)] = \log[u_i(1-u_i)] + 2\log(\tilde{s}_i^{1-\alpha} - \tilde{s}_j^{1-\alpha}) + 2\log\alpha$$

We plug in the expressions for $u_i = \frac{1-\tilde{s}_j}{\tilde{s}_i-\tilde{s}_j}$ and $1-u_i = \frac{\tilde{s}_i-1}{\tilde{s}_i-\tilde{s}_j}$ and linearly approximate the second term around $\tilde{s}=1$: $\tilde{s}^{1-\alpha} = 1+(1-\alpha)(\tilde{s}-1)$, then this proposition is equivalent to showing that

$$\begin{aligned}\frac{\partial V(w^u)}{\partial q} &= \frac{\partial}{\partial q}\left[\log(\tilde{s}_i-1) + \log(1-\tilde{s}_j) - 2\log(\tilde{s}_i-\tilde{s}_j) + 2\log(1-\alpha) + 2\log(\tilde{s}_i-\tilde{s}_j) + 2\log\alpha\right] \\ &= \frac{\partial\tilde{s}_i/\partial q}{\tilde{s}_i-1} - \frac{\partial\tilde{s}_j/\partial q}{1-\tilde{s}_j}\end{aligned}$$

From Proposition 2 we know that $\tilde{s}_i > 1 > \tilde{s}_j$ and from Proposition 8 we know that $\frac{\partial\tilde{s}_i}{\partial q} > 0$ and $\frac{\partial\tilde{s}_j}{\partial q} < 0$, so the above expression is positive. ∎

Proof of Proposition 5: $\frac{\partial Var(w^u)}{\partial q} > \frac{\partial Var(w^s)}{\partial q}$ Recall the formula for skilled wage dispersion:

$$\begin{aligned}V(w^s) &= s_i(1-s_i)(w_i^s - w_j^s)^2 \\ &= \tilde{s}_i\tilde{s}_j\left(\frac{w_i^s - w_j^s}{w_i^u - w_j^u}\right)^2 V(w^u) \\ V(w^s) < V(w^u) \Leftrightarrow \tilde{s}_i\tilde{s}_j &\left(\frac{w_i^s - w_j^s}{w_i^u - w_j^u}\right)^2 < 1\end{aligned}$$

So if we can show that $\tilde{s}_i\tilde{s}_j\left(\frac{w_i^u-w_j^u}{w_i^s-w_j^s}\right)^2 < 1$, then the result is shown. The first part of the expression is smaller than one. Note that $\tilde{s}_i\tilde{s}_j = \frac{s_i(1-s_i)}{u_i(1-u_i)}$. We know from Proposition 2 that $s_i > u_i \Leftrightarrow 1-s_i < 1-u_i$, so u_i is closer to 1/2. For any value x on the unit interval the expression $x(1-x)$ is maximized for $x = 1/2$. Since u is closer to 1/2 than s_i, it must be that $u_i(1-u_i) > s_i(1-s_i)$.

The second term is intuitive: since skilled workers migrate more, their wage differential will be not as wide as the unskilled workers' wage differential. $\blacksquare$

B Empirics

B.1 Data Set

B.2 Constructing Oil Shock measures

We follow Kilian (2009) and decompose the oil price into three components: movements driven by exogenous supply disruptions, movements drive by increased demand in U.S. industrial production and remaining movements. We are only interested in the first part, the exogenous components driven by changes in oil supply that originate outside the U.S.

B.3 Tables

Table 1: Weights in the CPI for Urban Consumers

Housing	42.7%	
Shelter & Utilities		33.7%
Fuels & HH equipment		9.0%
Transportation	17.2%	
Gasoline & Fuel		4.3%
Public Transportation		1.1%
Other		11.8%
Food and Beverages	15.0%	
Medical Care	6.3%	
Education and Communication	6.0%	
Recreation	5.6%	
Apparel	3.7%	
Other Goods and Services	3.5%	

Source: Bureau of Labor Statistics (2007), Ch. 7, App. 4

Table 2: Summary Statistics of Wage Levels and Energy Efficiency for establishments in the ASM 1972-2009

	Energy Intensity qe/y	Skilled Wages $\log(w^s)$	Unskilled Wages $\log(w^u)$
Average	0.0522	-0.5512	-1.7515
Standard deviation	0.0559	0.4214	0.4196
Inter-quartile range	0.0656	0.5268	0.5102
"Bottom quartile"	0.0051	-0.9314	-2.1228
"Median"	0.0328	-0.5499	-1.7643
"Top quartile"	0.0707	-0.4046	-1.6126
N	$2,060k$	$1,934k$	$2,059k$

Energy efficiency refers to the output share of energy inputs, skilled wages are defined as the wage bill of non-production workers per worker; unskilled wages as the wage bill of production workers per production hour worked. "Bottom quartile" is the average of the 24th and 26th percentiles; "Median" and "Top quartile" are defined analogously.

Table 3: Summary Statistics of Dispersion

	Average	Volatility over time St. Dev.	Volatility over time CV	Min	Max
Oil supply shock	—	0.0438	—	−0.1607	0.1040
Demand shock	—	0.0485	—	−1.1723	0.9374
Dispersion of unskilled hourly wages					
Overall dispersion	0.1524	0.0159	10.4%	0.1174	0.1746
Between-county dispersion	0.0544	0.0076	14.0%	0.0367	0.0658
Average within-county dispersion	0.0980	0.0155	15.8%	0.0643	0.1219
Dispersion of skilled wages					
Overall dispersion	0.1474	0.0360	24.4%	0.1132	0.2345
Between-county dispersion	0.0334	0.0082	24.4%	0.0231	0.0503
Average within-county dispersion	0.1139	0.0284	24.9%	0.0877	0.1841
Dispersion of energy intensity					
Overall dispersion	$1.44*10^{-3}$	$0.97*10^{-3}$	67.4%	$0.45*10^{-3}$	$3.94*10^{-3}$
Between-county dispersion	$0.64*10^{-3}$	$0.45*10^{-3}$	71.1%	$0.17*10^{-3}$	$1.81*10^{-3}$
Average within-county dispersion	$0.80*10^{-3}$	$0.52*10^{-3}$	64.8%	$0.26*10^{-3}$	$2.13*10^{-3}$

The oil supply shock is based on Kilian (2009) with a positive shock corresponding to a supply disruption, a higher oil price and lower labor demand. By construction, the shock has mean zero. The overall dispersion of wages, $\log w$, and energy intensity, eq/y, (Panel A) is defined as the variance and is decomposed into the between-county dispersion of average wages/energy intensity (Panel B) and the average within-county dispersion of wages/energy intensity (Panel C) according to equation (1) for every year. This table displays the average dispersion component over the years (column "Average"), how much each component of dispersion fluctuates (columns "Volatility"), the minimum and maximum years. The wage dispersion variables are constructed by weighting observations by establishment-level employment, energy intensity dispersion by establishment-level energy consumption.

Table 4: Oil Price Shocks and Unskilled Wage Dispersion

	(1)	(2)	(3)	(4)
	Weighted Wage Dispersion		Unweighted Wage Dispersion	
Oil Supply Shock	0.0283**	0.0213	0.0124**	0.00831
	(0.0124)	(0.0142)	(0.00534)	(0.00500)
	[0.0144]		[0.00594]	
Oil Supply Shock: Lag 1	0.0247*	0.0160	0.0180***	0.0134**
	(0.0142)	(0.0148)	(0.00469)	(0.00539)
	[0.0141]		[0.00473]	
Oil Supply Shock: Lag 2	0.00576		0.0151**	
	(0.0130)		(0.00558)	
	[0.0147]		[0.00565]	
Demand	-0.00359**	-0.00308*	-0.00101	-0.00108*
	(0.00172)	(0.00168)	(0.000599)	(0.000561)
	[0.00152]		[0.000588]	
Demand: Lag 1	-0.00394**	-0.00350**	-0.00127**	-0.00109*
	(0.00161)	(0.00154)	(0.000575)	(0.000600)
	[0.00160]		[0.000538]	
Demand: Lag 2	-0.00180		-0.000279	
	(0.00131)		(0.000654)	
	[0.00138]		[0.000651]	
Linear Year Trend	-0.000616***	-0.000550***	-0.000407***	-0.000399***
	(0.0000782)	(0.0000935)	(0.0000263)	(0.0000300)
	[0.0000917]		[0.0000296]	
Observations	36	37	36	37
Adjusted R^2	0.731	0.623	0.867	0.838

Robust standard errors in parentheses. Newey-West standard errors with one lag are in square brackets.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Effects of oil price shocks and output shocks on between-county dispersion of unskilled hourly wages. The first two columns weight observations by unskilled employment while the last two are unweighted. Standard errors are in parentheses.

Table 5: Oil Price Shocks and Skilled Wage Dispersion

	(1)	(2)	(3)	(4)
	Weighted Wage Dispersion		Unweighted Wage Dispersion	
Oil Supply Shock	-0.00191	-0.00151	0.0152	0.0133
	(0.0143)	(0.0129)	(0.0111)	(0.00878)
	[0.0145]		[0.0109]	
Oil Supply Shock: Lag 1	-0.00852	-0.0102	0.0144*	0.00751
	(0.00975)	(0.00937)	(0.00726)	(0.00802)
	[0.0101]		[0.00755]	
Oil Supply Shock: Lag 2	0.0116		0.0164**	
	(0.0128)		(0.00789)	
	[0.0142]		[0.00887]	
Demand	-0.000898	-0.00117	-0.00168*	-0.00175*
	(0.00161)	(0.00157)	(0.000869)	(0.000938)
	[0.00166]		[0.000874]	
Demand: Lag 1	0.00145	0.00132	-0.00115	-0.00119
	(0.00129)	(0.00130)	(0.00105)	(0.00115)
	[0.00144]		[0.00115]	
Demand: Lag 2	-0.000193		-0.00164	
	(0.00133)		(0.00119)	
	[0.00114]		[0.00101]	
Linear Year Trend	0.000678***	0.000654***	-0.0000660	-0.0000660
	(0.0000556)	(0.0000511)	(0.0000411)	(0.0000433)
	[0.0000618]		[0.0000479]	
Observations	36	37	36	37
Adjusted R^2	0.764	0.777	0.120	0.056

Robust standard errors in parentheses. Newey-West standard errors with one lag are in square brackets.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Effects of oil price shocks and output shocks on between-county dispersion of skilled wages. The first two columns weight observations by skilled employment while the last three are unweighted. Standard errors are in parentheses.

	(1)	(2)	(3)	(4)	(5)	(6)
	xvar32a_B	xvar32a_B	xvar32a_B	xvar1a_B	xvar1a_B	xvar1a_B
SupplSh_b	0.0181	0.0181	0.0154	0.165	0.165	0.160**
	(0.0335)	(0.0326)	(0.0246)	(0.119)	(0.123)	(0.0689)
lag_SupplSh_b	0.0221	0.0221	0.00557	0.149*	0.149	0.0693
	(0.0237)	(0.0247)	(0.0172)	(0.0828)	(0.0914)	(0.0875)
laglag_SupplSh_b	0.0358	0.0358		0.0993	0.0993	
	(0.0274)	(0.0297)		(0.0801)	(0.0803)	
GDPSh_c	-0.00283	-0.00283	-0.00297	-0.0165	-0.0165	-0.0154
	(0.00347)	(0.00335)	(0.00314)	(0.0106)	(0.0101)	(0.0106)
lag_GDPSh_c	-0.00683**	-0.00683**	-0.00704**	-0.0352***	-0.0352**	-0.0364**
	(0.00331)	(0.00321)	(0.00322)	(0.0127)	(0.0131)	(0.0135)
laglag_GDPSh_c	-0.00450	-0.00450		-0.0268*	-0.0268*	
	(0.00427)	(0.00434)		(0.0144)	(0.0146)	
YEAR	0.000675***	0.000675***	0.000673***	0.000170	0.000170	0.000287
	(0.000125)	(0.000146)	(0.000115)	(0.000430)	(0.000528)	(0.000409)
Observations	36	36	37	36	36	37
Adjusted R^2	0.355		0.366	0.185		0.113

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Effects of oil price shocks and output shocks on between county dispersion of unskilled workers. The first two columns weight observations on skilled employment while the last three are unweighted. Standard errors are in parentheses.

	(1)	(2)	(3)	(4)
	Between County Wage Dispersion: Weighted		Between County Wage Dispersion: Un	
Oil Supply Shock	0.0247	0.0232	0.192	0.187**
	(0.0345)	(0.0231)	(0.134)	(0.0765)
	[0.0335]		[0.140]	
Oil Supply Shock: Lag 1	0.0230	0.00779	0.107	0.0186
	(0.0216)	(0.0173)	(0.0952)	(0.0986)
	[0.0217]		[0.104]	
Oil Supply Shock: Lag 2	0.0364		0.106	
	(0.0281)		(0.0955)	
	[0.0303]		[0.0981]	
	-0.00311	-0.00338	-0.0172	-0.0159
	(0.00331)	(0.00292)	(0.0125)	(0.0123)
	[0.00316]		[0.0119]	
GDP: Lag 1	-0.00685**	-0.00715**	-0.0392***	-0.0405***
	(0.00315)	(0.00310)	(0.0138)	(0.0146)
	[0.00294]		[0.0144]	
GDP: Lag 2	-0.00417		-0.0299*	
	(0.00453)		(0.0175)	
	[0.00450]		[0.0178]	
Linear Year Trend	0.000687***	0.000671***	0.000216	0.000358
	(0.000130)	(0.000118)	(0.000502)	(0.000480)
	[0.000157]		[0.000610]	
Observations	36	37	36	37
Adjusted R^2	0.341	0.351	0.138	0.082

Robust Standard errors in parentheses. Newey West with one lag are in square brackets.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Effects of oil price shocks and output shocks on between county dispersion of unskilled hours. The first three columns weight observations on skilled employment while the last three are unweighted. Standard errors are in parentheses. For columns 2 and 5, standard errors are Newey West with one lag while in all other columns, they are simply robust.

	(1)	(2)	(3)	(4)	(5)	(6)
	xvar31a_B	xvar31a_B	xvar31a_B	xvar1a_B	xvar1a_B	xvar1a_B
SupplSh_b	0.0402	0.0402	0.00935	0.121**	0.121**	0.100**
	(0.0527)	(0.0527)	(0.0464)	(0.0558)	(0.0575)	(0.0449)
lag_SupplSh_b	0.0451	0.0451	0.0432	0.137***	0.137***	0.0962**
	(0.0362)	(0.0350)	(0.0474)	(0.0417)	(0.0437)	(0.0402)
laglag_SupplSh_b	0.0958*	0.0958*		0.0919**	0.0919**	
	(0.0469)	(0.0510)		(0.0396)	(0.0420)	
GDPSh_c	0.000715	0.000715	-0.000730	-0.00879	-0.00879	-0.00869
	(0.00445)	(0.00445)	(0.00436)	(0.00575)	(0.00552)	(0.00526)
lag_GDPSh_c	0.00260	0.00260	0.00440	-0.0112*	-0.0112*	-0.0106
	(0.00467)	(0.00472)	(0.00472)	(0.00619)	(0.00639)	(0.00624)
laglag_GDPSh_c	0.0104**	0.0104***		-0.00813	-0.00813	
	(0.00380)	(0.00359)		(0.00651)	(0.00695)	
YEAR	-0.00187***	-0.00187***	-0.00190***	-0.000403*	-0.000403	-0.000325
	(0.000170)	(0.000200)	(0.000177)	(0.000208)	(0.000239)	(0.000227)
Observations	36	36	37	36	36	37
Adjusted R^2	0.794		0.730	0.163		0.085

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Effects of oil price shocks and output shocks on between county dispersion of skilled workers. The first three columns weight observations on skilled employment while the last three are unweighted. Standard errors are in parentheses. For columns 2 and 5, standard errors are Newey West with one lag while in all other columns, they are simply robust.

Table 9: Effect of Oil Price Shocks on Wage Levels by Energy Use

	Skilled Wages				Unskilled Wages			
	Pooled OLS		Fixed Effects		Pooled OLS		Fixed Effects	
	energy intensity		energy intensity		energy intensity		energy intensity	
	low	high	low	high	low	high	low	high
Oil Shock	−0.2042**	−0.2250***	−0.2098***	−0.2504***	−0.0883	−0.1054	−0.1048***	−0.1417***
	0.0979	0.0787	0.0266	0.0162	0.0951	0.1210	0.0128	0.0074
Demand Shock	0.0287***	0.0380***	0.0316***	0.0295***	0.0245**	0.0357**	0.0222***	0.0221***
	0.0075	0.0095	0.0030	0.0019	0.0119	0.0165	0.0016	0.0011
Linear trend	0.0045***	0.0019***	0.0041***	0.0019***	0.0022***	−0.0021***	0.0020***	−0.0008***
	0.0004	0.0004	0.0004	0.0003	0.0004	0.0006	0.0002	0.0001
Constant	−9.4953***	−4.3478***	−8.6929***	−4.4166***	−6.1610***	2.4375 **	−5.8032***	−0.1804***
	0.7711	0.8366	0.7326	0.5455	0.8893	1.2031	0.3813	0.2836
N	$953k$	$981k$	$953k$	$981k$	$1,022k$	$1,036k$	$1,022k$	$1,035,600$

Effects of oil and output shocks on wage levels at the establishment level. Oil supply is an exogenous supply disturbance where a positive value *increases* the price of oil everything else equal. Standard errors are clustered at the year-level. Efficient versus inefficient are defined based on whether a particular establishment has above or below the median share of fuel in revenue.

	Labor							
	Skilled				Unskilled			
	Efficient		Inefficient		Efficient		Inefficient	
	Pooled	FE	Pooled	FE	Pooled	FE	Pooled	FE
Oil Supply	.070	.067	.060	.059	-.17	-.17	-.267	-.26
IP	.0082	.0053	.012	.014	.026	.029	.025	.028
N	772000	772000	778000	778000	824000	824000	822000	822000
R^2	.004	.0005	.0024	.0002	.0063	.0018	.0051	.001

Table 10: Effects of oil and output shocks on labor inputs. For the skilled category, the variable is number of non-production workers at the establishment-level. For the unskilled, the variable is total number of hours for production workers. Oil supply is an exogenous supply disturbance where a positive value *increases* the price of oil everything else equal. Standard errors are clustered at the year-level. Efficient versus inefficient are defined based on whether a particular establishment has above or below the median share of fuel in revenue.

B.4 Measurement Error and Robustness

- redo estimation with wage per unskilled employee; not different?
- in CPS, get MSA and county
-

C Figures

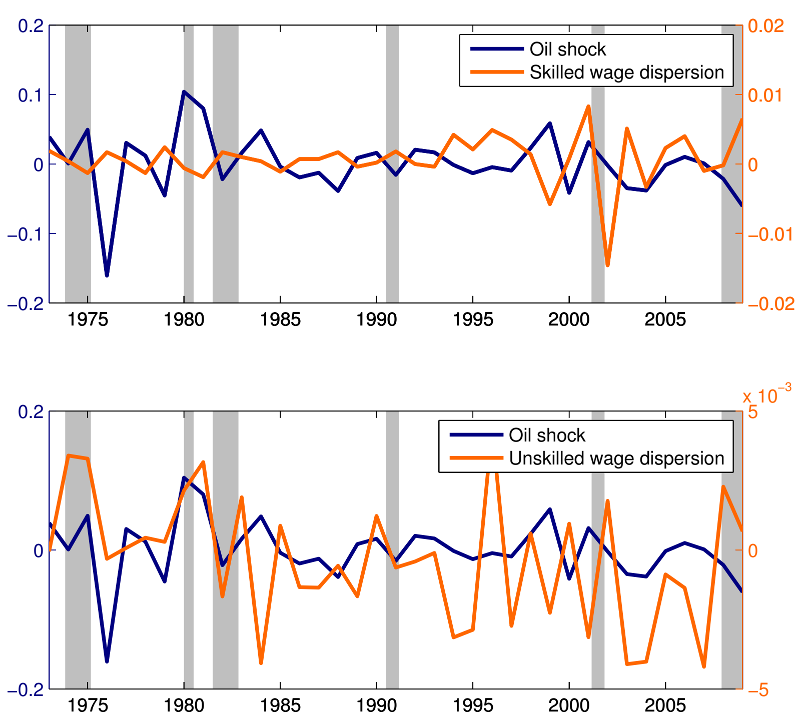

Figure 1: Oil Price and Between-County Wage Dispersion

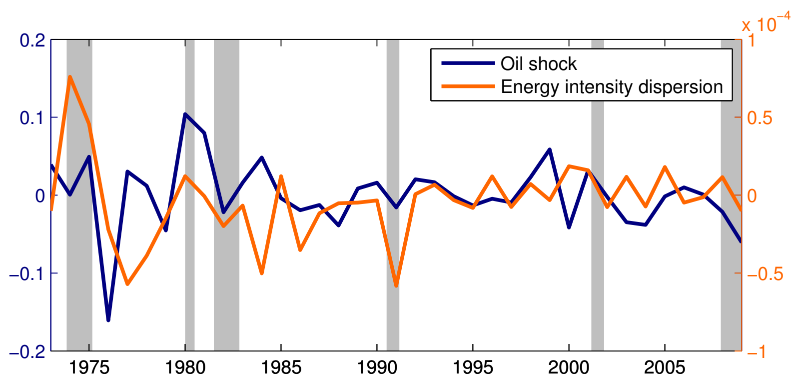

Figure 2: Oil Price and Between-County Energy Intensity Dispersion

All the following graphs have the following calibration: $\alpha = 0.35$ from labor literature, calibrated to match the income share of unskilled. $\beta = 3$ is a housing supply elasticity that reflects a convex housing supply curve.[28] The levels of energy intensity in the two regions is calibrated to achieve a coefficient of variation of 1/3 in energy intensity dispersion (measured as dollar spent per dollar value added). This can be obtained by choosing $\gamma_i = 2$ and $\gamma_j = 1$ – an assumption that implies only little difference in energy intensity in light of the empirics shown in Table 2, Panel B. $\theta^u = 0.5$ and $\theta^s = 0.25$ are the expenditure shares for housing of unskilled and skilled workers. They roughly correspond to the top and bottom quintile of housing shares in the CPS. As outlined in section 3.4, we focus on "small" values of q.

[28] Notowidigdo (2010) finds that *downwardly* the elasticity might be actually smaller than unity. This suggests a housing supply curve that is concave downwards.

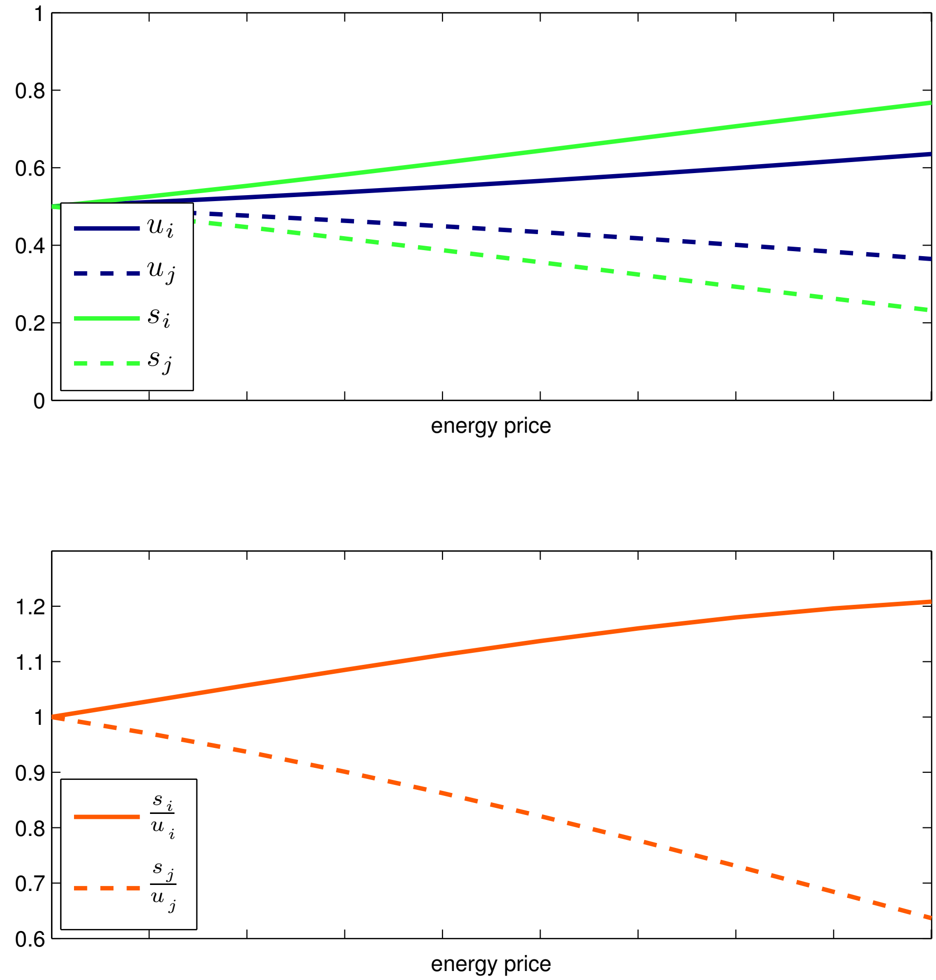

Figure 3: Labor Allocation

Model simulation of the allocation of skilled (s_i) and unskilled (u_i) labor across regions (top panel). Solid lines denote the allocation of unskilled (dark blue) and skilled labor (green) in region i, dashed lines the analogues in region j. Bottom panel depicts the skill intensities (s_i/u_i) in both regions. Note that the skilled allocation is always more skewed towards the more energy-efficient region (here: region i) than unskilled workers are. This is because the skill-energy complementarity implies that skilled workers are more affected by energy than unskilled workers are, which leads to more pronounced reallocation of skilled labor.

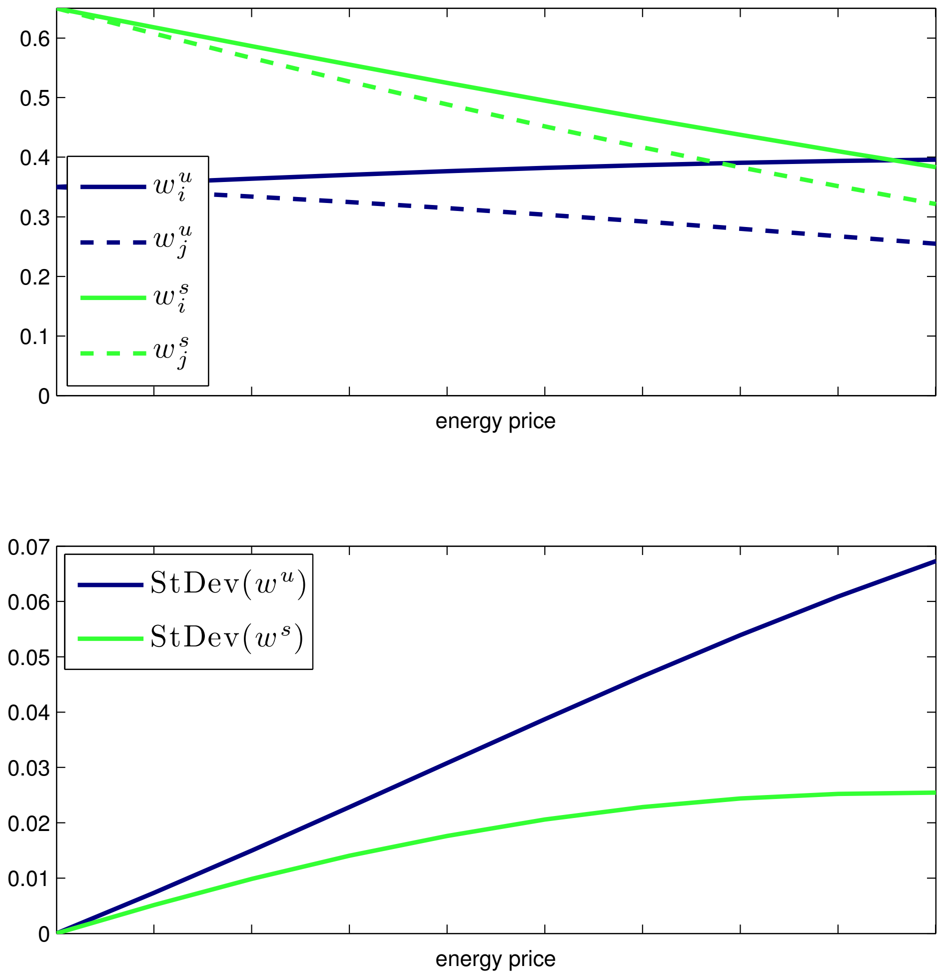

Figure 4: Wages and Wage Dispersion

Model simulation of the wage dispersion for unskilled (dark blue) and skilled (green) workers. Skilled wage dispersion is defined as (unskilled wage dispersion analogously)

$$StDev(w^s) = \left[\sum_{\ell=i,j} s_\ell (w_\ell^s - \overline{w}^s)^2 \right]^{\frac{1}{2}} .$$

Wages fall stronger for skilled workers because they are complementary to energy. All wages in region j fall (more) than wages in region i.
Unskilled wage dispersion increases more than skilled wage dispersion because unskilled wages are more different (see top panel) and unskilled labor reallocation changes less than skilled reallocation does (see Figure 3 top panel).

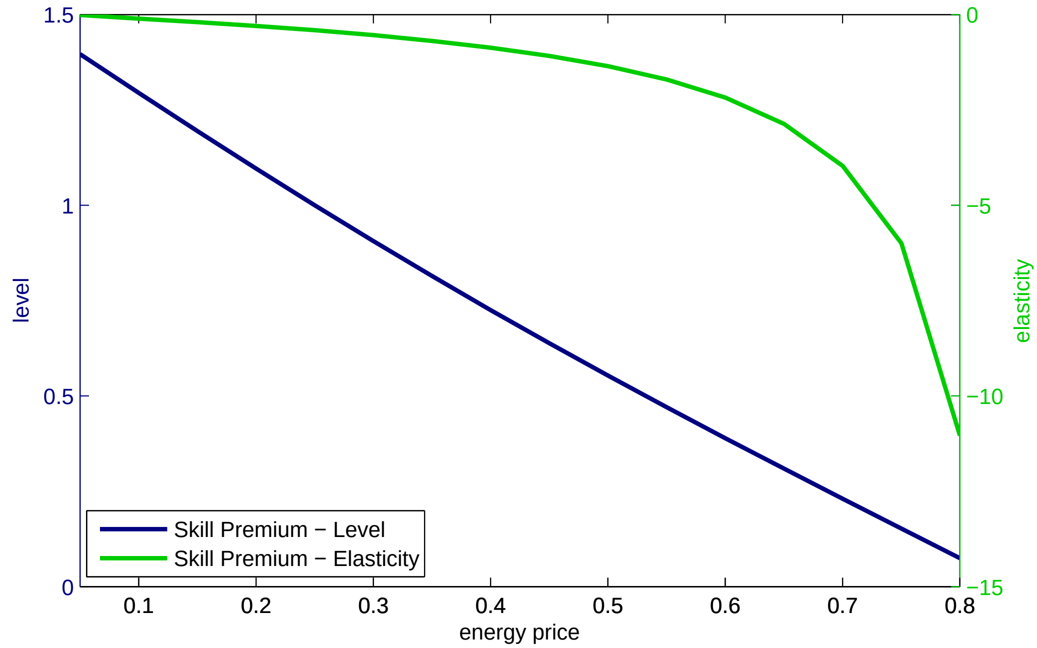

Figure 5: Skill Premium

Model simulation of the skill premium (orange) and average unskilled (dark blue) and skilled (green) wages. The result from Polgreen and Silos (2009), a falling skill premium with higher oil prices, is reproduced. Note that the skill premium may be smaller than unity which one could easily overcome by assuming skilled are in relatively scarce supply and/or are more efficient than unskilled workers.

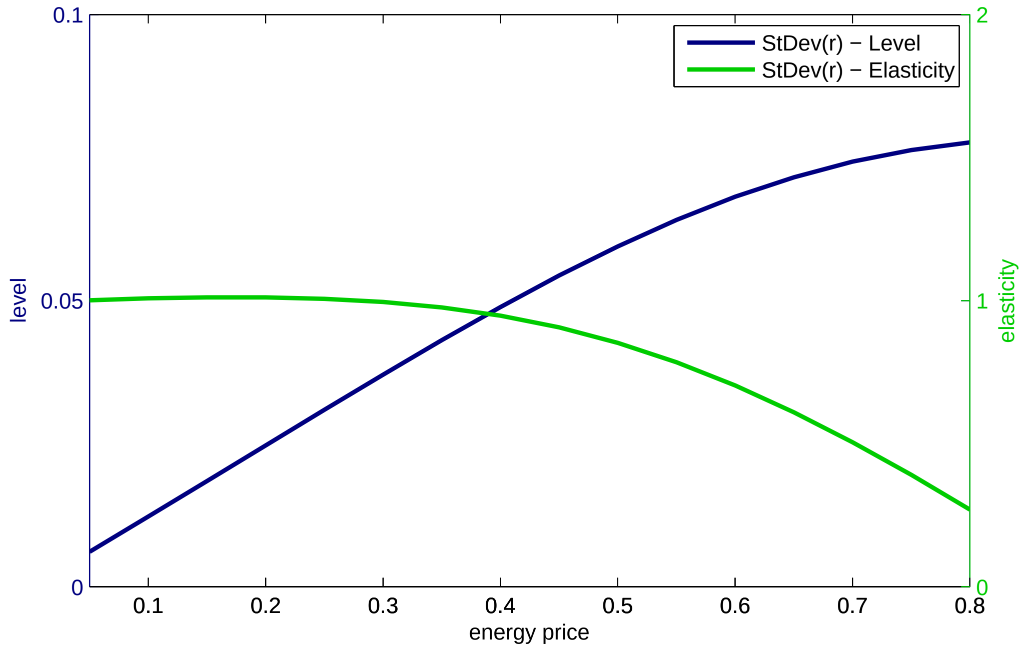

Figure 6: Housing Prices and Housing Price Dispersion

Model simulation of housing prices in both regions (blue and green) and the dispersion (orange). Housing price dispersion is computed like wage dispersion:

$$StDev(r) = \left[\omega_i(1-\omega_i)(r_i - r_j)^2\right]^{\frac{1}{2}}$$

where $\omega_i = \frac{H_i^D}{H_i^D + H_j^D}$ is the share of housing demand in region i in total housing demand. The rising housing price dispersion can only be supported in equilibrium because of wage dispersion.